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FOREIGN TECHNOLOGY DIVISION

LUBRICATING OILS FOR JET ENGINES
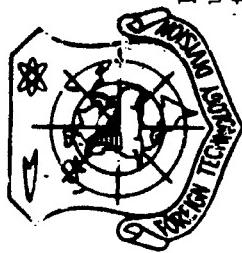
by

Ye. N. Kalaytan

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EDITED TRANSLATION

LUBRICATING OILS FOR JET ENGINES

By: Ye. N. Kalaytan

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Abstract

This book describes briefly the construction and principles of operation of aviation gas turbine engines, their assemblies and friction points, and also the oil systems. Operating conditions cf lubricants in these engines are discussed, as are the functions of oils as lubricating materials, the functions of operating liquids and cooling agents; technical specifications required of lubricants are discussed.

Questions are discussed related to the assortment and quality of oils currently employed for aviation gas turbine engines and the requirements for oils of the near future.

Methods are described for obtaining from petroleum and synthetics high-quality oils which possess high antioxidation, viscosity-temperature, anti-wear and other properties.

Information is presented concerning additives which improve the operational properties of oils for aviation gas turbine engines. Domestic and foreign methods of investigating and testing oils under laboratory conditions, and also in special stands and devices are systematized and described.

This book is intended for specialists associated with the construction and operation of aviation gas turbine engines, for petroleum engineers and chemists who are involved in the processing and preparation of the oils indicated and additives for them, and also for students of aviation and petroleum institutes and technical schools.

The book contains 91 tables, 43 drawings, and 200 bibliographical references.

Introduction

The last decades have been marked by the rapid growth of jet aviation, which in a short time has occupied a leading place in contemporary aviation technology. The successful development of this type of aviation was caused by the development and application of aviation gas turbine engines (AGTD), which have facilitated the high speeds of contemporary aircraft and the significant altitude of their flights. Thus in foreign aviation aircraft speeds have achieved Mach 3[1] with a ceiling of 30 km and above. The first planned and constructed supersonic passenger aircraft of types including the domestic TU-144 liner or the foreign "Concord" aircraft are designed for speeds to 2500 km/hr at a ceiling of 25-30 km and a nonstop flight distance of the order of 6500 km.

In comparison with piston aviation engines, the AGTD have a number of operating advantages, including greater power in thrust with relatively less weight and dimensions. This has facilitated the wide employment of the AGDT in aviation technology. In high-speed, supersonic aviation, power-boosted turbojet engines (TRD) are employed, the operating conditions of which are characterized by high temperatures and heavy loads on the operating parts of the engines. In heavier aircraft, designed for long-distance flights at subsonic speeds, turboprop engines (TVD) are installed in which the thermal stress is less than in the TRD, but greater than in aviation piston engines.

For contemporary AGTD stable, high-quality lubricants are required which are capable of an extended period of operation in these engines at high temperatures without significant deterioration in quality. Thus according to foreign data, lubricants for thermally stressed TRD must be stable at 175-200°C; oils for TRD of the near future must be capable of operation to temperatures of 250°C and higher. In this connection a great deal of work has been accomplished recently devoted to the development of such oils on the basis of petroleum and synthetic products. However, notwithstanding this, the quality of lubricants for AGTD still does not correspond to all the requirements established for it, which in a number of cases interferes with increasing engine resources and the perfection of newly developed engines.

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[1]See p. 3

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Therefore the problem of developing high-quality lubricants for AGTD is quite pressing. In the USSR, as in other countries, it is closely associated with increasing the reliability and lengthening the life of the AGTD, which is an important economic problem.

In connection with the increased requirements applied to lubricants for the AGTD, the majority of methods previously applied in the investigation of the quality of turbojet oils, especially synthetic ones, proved to be unsuitable. Therefore at the present time both in the USSR and abroad a great deal of attention is being devoted to the development of new laboratory and static methods of evaluating the physicochemical and operating properties of these oils.

In connection with what has been stated, the necessity arose to generalize and systematize domestic and foreign materials available on the problems of development, investigation of quality and the application of petroleum and synthetic oils for the AGTD.

Continuously developing jet aviation may be provided with the required high-quality lubricants more quickly with the combined work of designers and specialists who develop and apply lubricants for AGTD. Therefore problems in the development and improvement of lubricating oil quality are examined in this book in close connection with the conditions of their exploitation in these engines.

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Footnotes

1. To p.1. The Mach number is the ratio of the speed of flight of a device to the speed of sound, equal to 1194.5 km/hr at 0°C and atmospheric pressure.

CHAPTER ONE

A SHORT SURVEY OF THE TYPES OF AVIATION GAS TURBINE ENGINES, THEIR CONSTRUCTION CHARACTERISTICS AND CONDITIONS OF OPERATION

Turbojet and Turboprop Engines

Jet engines are the base of the power installations of contemporary flying apparatus; they can be divided into two classes according to the principle of obtaining the operating mixture, which include rocket and air-breathing engines (VRD).

A special oxidizer is employed in rocket engines for fuel combustion. According to the type of fuel employed, these engines are divided into liquid-fuel engines and solid-fuel engines. Rocket engines have no special lubricant systems and will not be discussed further.

As a source of oxygen air-breathing engines employ air, which is compressed upon passing into the engine and is then directed to the chamber where combustion of the operating mixture occurs [1-3].

Depending on the method of increasing the air pressure, VRD are divided into compressor and noncompressor engines. The latter, which have no turbo-compressor assembly (ram jets and pulse jets) and special lubrication systems, are also not examined further. In turn, aviation gas turbine engines (AGTD) which have turbocompressor assemblies are divided into turboprop (TVD) and turbojet (TRD) engines. The principal difference between the turboprop and the turbojet engines is the presence of the air screw and the reducer, which reduces the number of revolutions from the gas turbine shaft to the air screw [4-5].

Axial or centrifugal compressors are employed in the AGTD to compress the entering air; engines with axial compressors, which have smaller dimensions, are the most widely employed. A diagram of a contemporary TRD with an axial compressor is shown in Figure 1 [6]. The operating principle of the TRD is as follows. Atmospheric air (see Figure 1) enters through the input part (1) of the engine for compression in compressor (2). The air,

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compressed to the required pressure, is directed to combustion chamber (3),
to which atomized fuel is simultaneously directed through the injectors.
Gases which form in the process of combustion pass from chamber (3) to
turbine blades (4), cause the turbine to rotate and then pass into after-
burner (5). The purpose of the afterburner is to furnish a short-duration
increase in engine thrust, achieved by burning in the chamber supplementary
quantities of fuel. Expanding in reaction nozzle (6), the gases escape into
the atmosphere with great force and create a reactive thrust [7-8]. An
external view of a TRD with an axial compressor is shown in Figure 2.
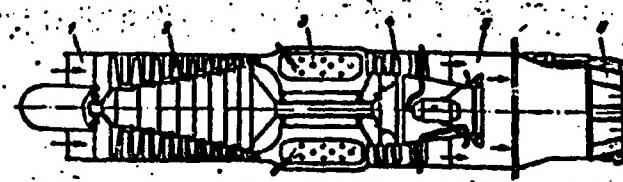
Figure 1. Diagram of a TRD with an axial compressor: 1, Input
part of the engine; 2, Axial compressor; 3, Combustion chamber;
4, Turbine; 5, Afterburner; 6, Reaction nozzle

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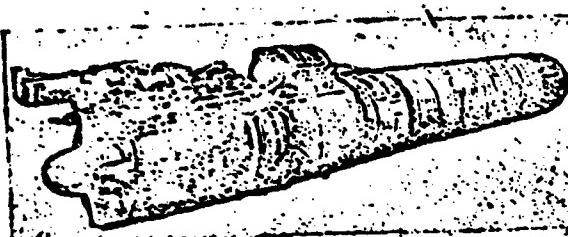
Figure 2. An overall view of a TRD with an axial compressor

In the TRD the gas turbine serves to rotate the compressor and to set in
motion a large number of different assemblies. In the TVD the gas turbine,
in addition, rotates the air screw and therefore must develop higher power
than in the TRD. A diagram of the TVD is shown in Figure 3.

Thrust in the TVD is created basically by means of the air screw and
exceeds the thrust of the direct reaction of the gases by 7-10 times;
the fraction of power expended on the rotation of the air screw and on
reactive thrust depends on the speed of the aircraft.

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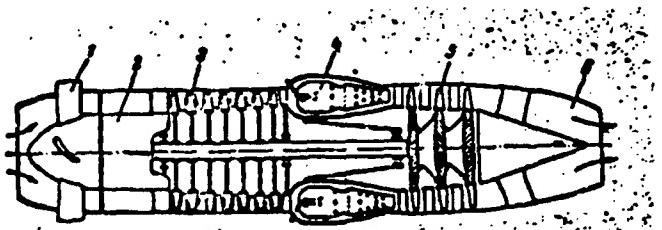
Figure 3. The fundamental design of the TVD: 1, Air screw;
2, Reducer; 3, Compressor; 4, Combustion chamber; 5, Turbine;
6, Reaction nozzle

In a contemporary TVD the number of revolutions of the turbocompressor
assembly is from 7000 to 18,000 per minute, whereas the air screw, in order
to obtain maximum efficiency at the design flight condition, must rotate with
a speed of 750 to 1500 rpm. Therefore in order to reduce the number of
revolutions transmitted from the turbocompressor shaft of the TVD to the
screw, special reducers are employed. These reducers are high-load systems,
characterized by a complex kinematic diagram, small dimensions and low
weight, and by high efficiency.

In order to provide for reliability in operation and to reduce wear of
the gears in the reducers, it is necessary to employ oils which possess high
lubricating capability.

An overall view of the TVD is shown in Figure 4 and diagrams of
different reducers are shown in Figures 5-7.

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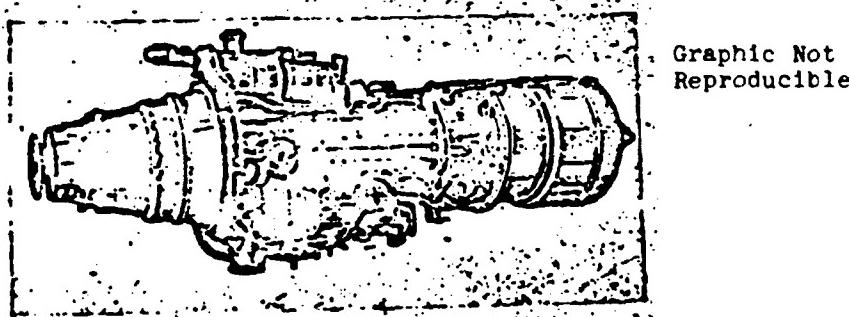
Figure 4. An overall view of the TVD with an axial compressor

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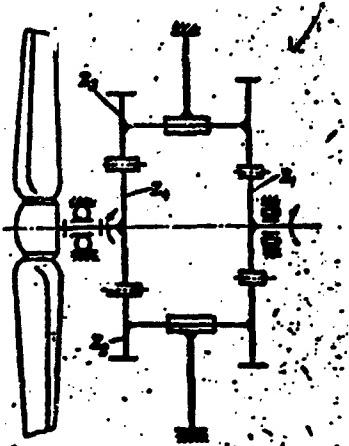
Figure 5. Diagram of a simple reducer for a single screw drive: z_1, z_2, z_3, z_4 are gears.
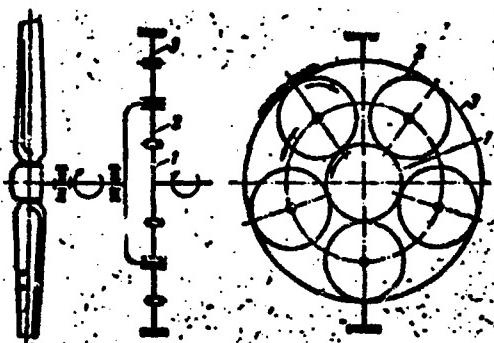
Figure 6. Diagram of a planetary reducer for a single screw drive: 1, Driving gear; 2, Satellite gear; 3, Stationary gear

In the AGTD the basic assemblies and friction points which require lubrication are the ball and roller bearings of the turbocompressor assembly; the reducer gear of the power takeoff; drive gears of assemblies operating at high rpm; slotted shaft couplings, and in the TVD, in addition, there are also the gears of the reducer. A representation of the number of lubricated gears in the drive assemblies alone of a TRD with an axial compressor is shown in Figure 8.

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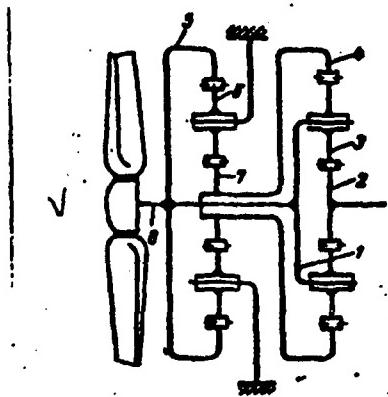
Figure 7. Diagram of a differential reducer: 1, Satellite
carrier; 2, Driving gear; 3, Satellite gear; 4, Gear with internal
toothing; 5, 7, Gears; 6, Idle gear; 8, Screw shaft
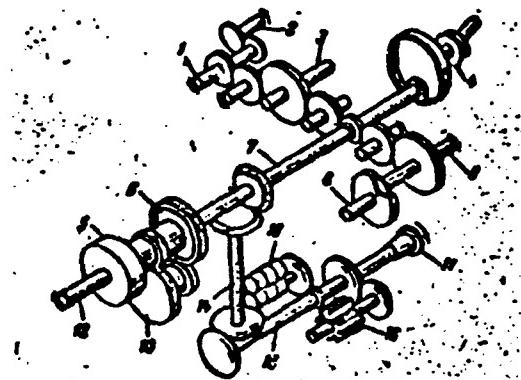
Figure 8. A kinematic diagram of the drive assemblies of a
turbojet engine with an axial compressor: 1, Booster pump drive;
2, Centrifugal valve drive; 3, Fuel pump drive; 4, Hydropump
drive; 5, Friction coupling; 6, Roller coupling; 7, Turbocompressor
shaft; 8, Oil assembly drive; 9, Fuel pump drive; 10, Oil pump
(exhaust); 11, Connecting coupling; 12, Starter-generator drive;
13, Ratchet coupling; 14, Spring; 15, Drive shaft; 16, Centrifugal
breather

The high-rpm turbocompressor presents the most rigid requirements for
quality in the oil employed (starting and antioxidation properties).

Oil Systems

Lubricating oil in the AGTD reduces friction and wear on parts and assemblies, removes heat from them, prevents the appearance of corrosion and galling (hardening), removes hard impurities and particles which appear between rubbing parts. In some TRD oil serves as an operating liquid (automatic and control systems) and is employed in servomechanisms [9]. Structurally the AGTD oil systems are constructed accordingly. With low oil consumption the AGTD lubrication system, air tight, compact and displaying a low hydraulic resistance, must reliably provide for lubrication of the engine in any position of the aircraft and under any external conditions, including first of all temperature and pressure. Bearings under load, which are the most important, and also toothed and slotted couplings are subject to forced lubrication under pressure, which is provided by means of centrifugal or jet injectors. The remaining friction parts are lubricated by an oil spray, which is applied to rotating parts and which forms an oil mist.

In order to reduce the length of time the oil stays in the engine (with the aim of reducing heating, air saturation, and reducing contact time with metal), AGTD oil systems operate in accordance with the dry sump principle: after lubrication the oil is not accumulated in settling tanks in the engine housing, but is immediately pumped into an oil tank or into a main line for filtration, cooling and other operations.

Contemporary AGTD practice is to employ circulating closed (single-circuit or dual-circuit), open and combination lubrication systems [11-12]. The lubrication system design has a significant influence on the maximum ceiling of a jet aircraft. With an increase in altitude, oil foaming in the lubrication system increases; the oil pump output is reduced and as a result oil pressure in the system falls and engine lubrication is disrupted. Tests abroad have revealed that in high-altitude flights the closed-circuit oil circulating system is the most reliable -- it provides for the required engine lubrication to altitudes of 30 km and above.

The most economical and structurally simple single-circuit closed lubrication system, where the oil continuously and repeatedly circulates through a closed system, is the tank-engine-tank system. The open system of lubrication is usually employed in single-use engines, in which the oil is

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only used once. Such systems are very simple and the oil in these systems
after a single use is discarded to the atmosphere. In high-temperature TRD
in a number of cases open systems are employed for the lubrication and
cooling of the most highly stressed bearings, where the oil undergoes
significant changes; after a single lubrication the oil is also discharged
from the engine to the atmosphere. Parts and bearings heated to a lesser
degree are serviced by the usual closed system. Such oil systems are called
combined systems.

Notwithstanding diverse AGTD designs, their lubrication systems are for
the most part standard and consists of assemblies which are similar in
purpose.

AGTD lubrication systems usually include the following elements: the
oil tank, oil radiator, oil pumps, oil filters, the air separator, reduction
valve, shut-off valves, oil injectors, the oil line and devices for the
control of oil temperature and pressure. A typical diagram of a closed
lubrication system in a contemporary TRD is represented in Figure 9 [9].
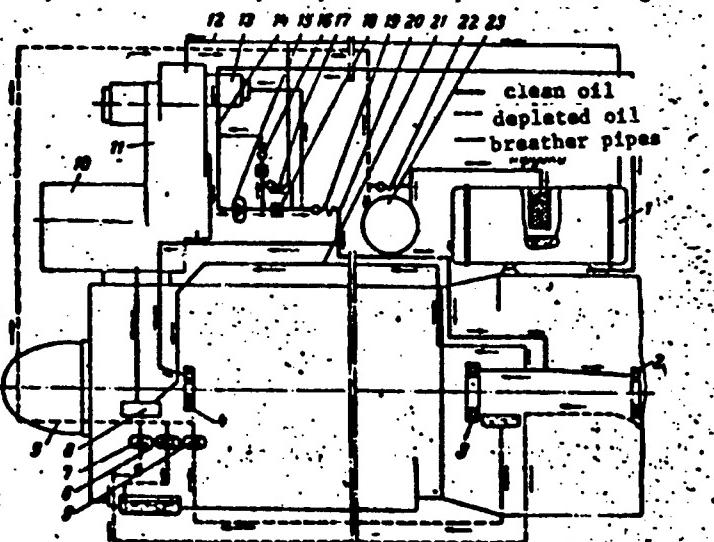
Figure 9. Diagram of TRD lubrication system: 1, Oil tank; 2, Turbine
bearing; 3, 4, Front and rear compressor bearings, respectively;
5, 6, 7, Pumping out stages of oil pump; 8, Centrifugal breather;
9, 20, Pipelines; 10, Two-speed drive; 11, Assembly housing;
12, 14, 21, Channels; 13, Cengrifugal valve; 15, Pressure oil pump;
16, Reduction valve; 17, Safety valve; 18, Fine-cleaning filter;
19, Check valve; 22, Valve; 23, Fuel-oil radiator

From oil tank (1) oil passes through oil line (14) to pressure pump (15) (which is part of the engine oil assembly), then passes through fine-cleaning filter (18) which is situated in the line and enters the cavity in the cover of the oil assembly. When a specified pressure is exceeded in the main oil line, the reduction valve passes oil to the input of pump (15) and when filter (18) is clogged the oil bypasses the filter and passes through valve (17) to the engine main oil line. From the oil assembly the bulk of the oil passes through check valve (19) (which does not permit oil to flow from the tank to the main oil line with a nonoperating engine) and is directed under pressure to the main oil channel of the assembly housing. Part of the oil from the housing cover cavity of these assemblies goes to centrifugal valve (13) and to an electromagnetic valve.

From the main oil channel of the assembly housing oil passes along pipeline (20) in several directions through a tee in order to lubricate the following friction points: the nose at the front compressor housing and front compressor bearing (4); assembly housing (11) and two-speed drive (10); rear compressor bearing (3) and turbine bearing (2).

All rotating parts and points of the housing for the assemblies, the two-speed drive, and the nose of the front compressor housing are lubricated under pressure; the front and rear bearings of the compressor (4) and (3) and also turbine bearing (2) are lubricated by oil under pressure through injectors with special jets. Individual gears are lubricated by spraying.

Depleted oil from rear compressor bearing (3) and turbine bearing (2) is gathered in settling tanks and is then pumped from the tanks by two stages (5) and (7) of the oil pumps through pipeline (9) into fuel-oil radiator (23) for cooling. Oil is pumped to this location through pipeline (9) from pumping-out stage (6) of the oil pump from the housing of the assemblies, from the nose of the front compressor housing and from front compressor bearing (4) (the oil settling tank of the front compressor housing).

The oil is cooled in fuel-oil radiator (23) as a result of heat transfer to fuel passing through the pipes, and in addition partial separation of air from the oil also occurs here. At increased hydraulic pressure in the radiator, valve (22) bypasses oil from the input main line to the output. Cooled and cleaned oil from the radiator passes into oil tank (1). It should

be pointed out that the presence of an oil radiator in the lubrication system
of a contemporary AGTD is not always obligatory.

The cavities of both compressor bearings and of the turbine bearing are
connected by breather (6) to channel (21), and the oil tank cavity, by
channel (12). Air extracted from the oil is vented to the atmosphere.

In many AGTD designs, a closed system of lubrication is employed in
which the lubricating oil, bypassing the oil tank of the aircraft, circulates
in a closed circuit. In this case the purpose of the oil tank is to refill
continuously to the normal level to compensate for oil losses in the engine
system caused by penetration of oil through the labyrinth seals, carrying
this oil off through the breathing system, and also to compensate for
evaporation.

The lubrication system for the domestically produced TVD AT-20A
(Figure 10) may serve as an example of a short-circuit system of lubrication.
Lubrication is accomplished by the following manner in this engine. Oil from
the pressure section (12) of the oil pump passes through filter (10) and
enters the oil system: 1) in order to lubricate the reducer and its parts;
2) in order to lubricate the rotor turbine bearings (3), assemblies and their
shafts, and also as an operating liquid for such assemblies as the airscrew
speed regulator, the command-fuel assembly, etc.

Depleted oil from the drive shaft housing of the aircraft assemblies is
evacuated by pump (15) to oil pan (17), which is situated in the lower part
of the front compressor bearing housing. The oil appears here by gravity
flow from the reducer, the front compressor bearing and the central drive
housing. The oil is evacuated from the cavities of the front compressor
bearing and the turbine bearing by two sections (19) of the oil pump and is
directed to the centrifugal air separator (21), which also receives oil from
oil pan (17). After removal of the air the oil is cooled in air-oil
radiator (22) and is again directed to pressure section (12) of the oil pump.

Loss of oil in the oil system is replenished by oil delivery from the
oil tank by means of additional supply pump (14) until restoration of the
specified value of oil pressure at the input to the pressure oil pump.
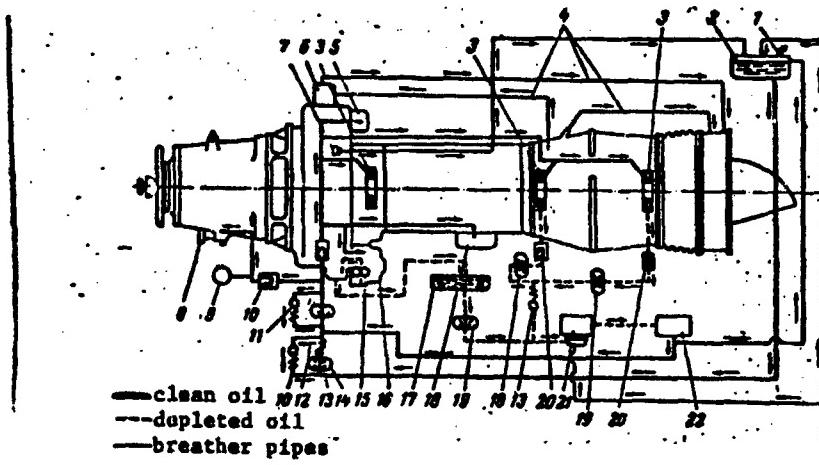
Figure 10. Diagram of the TFC AI-20A lubrication system: 1, Oil
tank breather; 2, Oil tank; 3, Bearings; 4, Breather pipes;
5, rpm regulator; 6, Centrifugal breather; 7, Central drive
breather; 8, Torque meter oil pump; 9, Manometer to measure oil
pressure; 10, Fine-cleaning oil filter; 11, Reduction valves;
12, Pressure section of the oil pump; 13, Check valves;
14, Additional supply pump; 15, Evacuating oil pump; 16, Drive
assembly casing; 17, Oil pan; 18, Command-fuel assembly;
19, Evacuating section of the oil pump; 20, Coarse-cleaning oil
filter; 21, Air separator; 22, Air-oil radiator

Breathing of the oil cavities of the front bearing housing and the
central drive is accomplished through the oil tank, and breathing of the
cavities of the rear compressor bearing and the turbine bearing is accom-
plished through centrifugal breather (6).

We have described above only a few typical TRD and TVD oil systems.
Other versions also exist; nevertheless the description given gives a
sufficiently clear representation of the operating fundamentals of the
systems and of the methods of cleaning working lubricating oil in an engine
(filtration, air separation, cooling, etc.) [13].

In engine friction points and in the oil system the properties of the
oil employed change during the operating process. It is possible to make a
judgment concerning these conditions (an increase in viscosity, a deterior-
ation of thermal oxidation stability, etc.) according to the condition of
individual assemblies of the oil system without disassembly of the engine.

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Thus oil foaming may be judged by operation of the oil pumps and the pressure which they create; the cleanliness of filter elements within the oil filters indicates the degree of oxidation of the working oil, etc.

Basic Oil System Assemblies, the Influence of Operating Conditions on Oil Quality

Oil Pumps

Gear pumps are used to deliver oil under pressure to rubbing parts and to evacuate oil from them; pump output attains values of 350 t/min. An oil pump consists of a pressure and several evacuating sections, and the evacuating sections must have two-three times greater output than the pressure sections. This is explained by the fact that foaming oil reaches the evacuating sections, and this oil has a large volume due to air content. The output of pressure oil pumps is usually two-three times higher than required, which is necessary in order to provide normal oil delivery to rubbing points at an altitude at which the output of the pump decreases. In AGTD oil systems a specifically established pressure of 3.5 to 5 kg/cm^2 is maintained by means of a special reduction valve installed in the main oil line. Therefore in evaluating the possibility of oil foaming and vaporization in the process of operation in an engine it is not necessary to examine the entire oil system or the oil line, but the individual assemblies (for example, the oil tank) of the oil system and those parts which are lubricated by means of spraying.

Oil Filters

Oil system filters are designed for cleaning from the oil harmful impurities and contaminants -- metal particles (products of wear of rubbing parts), dirt and gummy substances and also hard particles which are products of intensive oil oxidation during extended operation in an engine.

In practice it is possible to judge from the deposits on the filter screen not only the anti-wear properties of the oil, but also its capability to resist oxidation.

Oil filters are employed in pressure and in evacuation lines. In a pressure main line, a low-pressure filter is installed before the pump, and a high-pressure filter is installed after the pump. In an evacuation line

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filters may also be installed both before and after the pump. A diagram of
an oil filter is shown in Figure 11.
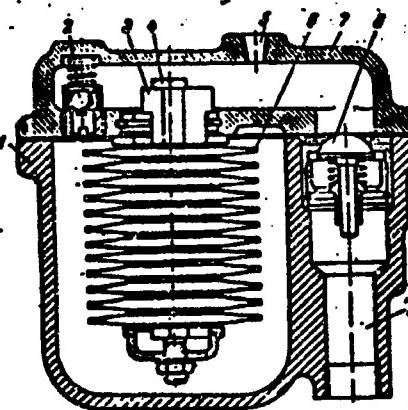
Figure 11. A diagram of a disk-strainer oil filter: 1, Housing;
2, Safety valve; 3, Frame; 4, Coupling bolt; 5, Place to measure
pressure; 6, Filtering disks; 7, Filter cover; 8, Shut-off valve;
9, Main line oil exit from the filter

The most widely employed filters in an AGTD are disk-strainer filters;
the fundamental operating parts -- the filtering elements -- are disks of
brass or steel wire with the number of cells ranging from 225 to 5000 per
1 cm^2. The disks are coated on a hollow frame.

The oil enters the filter and fills the annular cavity which is
situated around the filtering element, passes through the strainers, is
filtered and passes through the frame to the oil line. Filtered impurities
remain on the surface of the screens and may be evaluated quantitatively and
qualitatively. The filtering element is usually washed in gasoline. The
filter may be removed without spilling any oil by removing the filter cover.

In order to prevent rupture of the filter screen when the oil filter is
clogged with deposits, it is equipped with a safety valve. The permissible
pressure on the filter is from 1.3 to 1.5 kg/cm^2.

The Air Separator

One of the basic assemblies of the AGTD oil system is the air separator,
which is installed in order to eliminate gases from the oil.

It is known that foaming oil, saturated with gas, has a large volume; this reduces the output of oil pumps and the pressure in the oil system and in the final analysis may disrupt normal lubrication of rubbing parts in the engine. Foaming oil has reduced thermal conductivity and shows degraded performance in removing heat from hot engine parts. In additon, it is cooled unsatisfactorily in the radiator, as a result of which the overall oil temperature may rise, and this in turn will cause a deterioration in heat removal from engine parts.

Due to the large amount of oil pumped through the system and the significant gas content, the air separator must have a high output. Therefore it is advantageous to employ centrifugal air separators in the AGTD, which operate on the principle of a centrifuge.

The basic operating element of a centrifugal air separator is a rotating rotor, consisting of a shaft with a vane, which is placed in a special housing with cavities. Oil is delivered by the evacuation pump through one of the cavities of the housing and strikes the outside of the air separator rotor, and under the influence of centrifugal force is thrown to the periphery; from here the oil exits through another cavity to the oil line and then passes to the oil radiator. Air removed from the center of the rotor through an annular cavity is directed to the air space of the oil tank. A diagram of a centrifugal air separator is shown in Figure 12.

Oil Injectors

Oil is measured and delivered in spray form to turbocompressor assembly bearings in the AGTD by means of centrifugal or jet injectors. In a centrifugal oil injector, oil under the pressure of the pressure pump passes through a screen and through a spiral channel of the sprayer shaft (where the jet is twisted) and strikes the calibrated opening of the injector housing and is sprayed on the bearing. A shortcoming of injectors of this type is saturation of the oil spray with air, as a result of which heat removal from the bearing deteriorates. Therefore the most widely employed jet injectors which are simple in design are pipes with calibrated apertures with a diameter of 1-1.5 mm, from which the lubricating oil is directed to the bearing in the form of a sprayed jet under pressure.
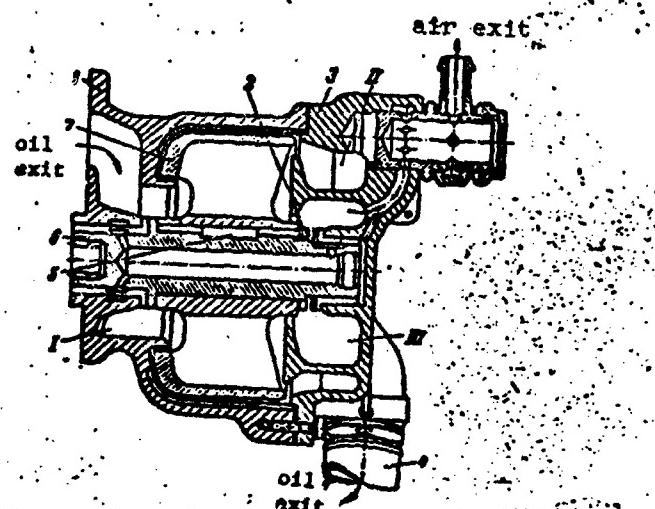
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Рис. 12. Схема центробежного воздухоотделителя:
1—корпус; 2—гайка; 3—крышка; 4—штуцер; 5—шлицы; 6—валик; 7—крыльчатка.
I—III—полости.

Figure 12. A diagram of a centrifugal air separator: 1, Housing;
2, Nut; 3, Cover; 4, Fitting; 5, Spline; 6, Shaft; 7, Vane.
1-3 are cavities.

When products of intensive oxidation appear in the lubricating oil in
the form of soft and abrasive deposits, the injectors are often coked, as a
result of which oil delivery to the bearing is reduced. This may lead to
burning of ball or roller bearings and to their failure.

The passage of oil through injectors, removed after engine operation, is
usually checked on special pumping stands; a reduction in oil flow, in
comparison with authorized specifications, indicates a shortcoming in its
thermal oxidation stability. A diagram of an injector used for the lubrica-
tion of bearings is shown in Figure 13.

The Breathing System

The breathing system of the engine represents a device which connects
the air space of the oil tank and the oil cavities with the atmosphere. If
this system is disrupted, lubricating oil losses may increase significantly.

Engine breathing is required for normal engine operation; with a lack of
breathing, heating and vaporization of the oil, and also a breakthrough of
gases into the oil cavities through labyrinth seals will cause an increase in
pressure in the oil cavities and in the engine oil tank, and in the final
analysis, may lead to throwing oil out of the system. In contemporary

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AGTD designs, the oil cavities are usually connected to the atmosphere by means of a breather, which is a channel containing partitions allowing air and oil vapors to pass freely, but which oppose the exit of oil.
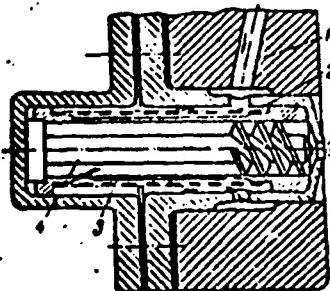
Figure 13. A diagram of a centrifugal oil injector: 1, Channel; 2, Screen; 3, Sleeve; 4, Shaft

At the present time centrifugal breathers are the most widely employed, which are similar in principle of operation and design to the centrifugal air separators described above. The mixture of air and oil vapors passes from the engine to a rotating vane; the oil is thrown by centrifugal force to the sides of the breather housing and drains along a special thread through a discharge nozzle to the engine. The air which is released passes through the cover of the breather and is vented to the atmosphere through a special channel.

With an increase in engine breathing or with inexact separation in the breather of oil vapors and air, oil loss in the form of vapors increases. Cases are known of an increase of 40-60% in lubricating oil consumption for 200-hour bench tests due to an increase in engine breathing. Therefore the engine breathing system requires careful observation.

CHAPTER TWO

THE PURPOSES OF LUBRICATING OILS AND THEIR QUALITATIVE REQUIREMENTS

Oil Operating Conditions

In contemporary AGTD designs oil lubricates rubbing parts, removes heat from them, acts as an operating fluid in various systems of manual and automatic control, and also protects the engine from corrosion in the operating state and while stopped or while in storage.

In connection with AGTD design considerations, operating conditions for these lubricating oils differ significantly from operating conditions in internal combustion piston engines. The basic operating characteristic of lubricating oil in all AGTD systems is the closed, continuous and multistage circulation of relatively small quantities for an extended period of time [14-15].

The basic operation assembly of the AGTD -- the turbocompressor -- is installed on ball and roller antifriction bearings and therefore the basic type of friction in the AGTD is rolling friction. It is known that the coefficient of friction for antifriction bearings is in the range 0.001-0.004, whereas for the usual sliding bearings this value reaches approximately 0.01. In contrast to piston engines the shaft of the trubocompressor assembly is well balanced and, notwithstanding the large number of revolutions and the high axial and radial loads, operates without sharply changing loads. This permits employing relatively low-viscosity oils for TRD lubrication (with a kinematic viscosity at 50°C of 6-10 cs). In addition to turbocompressor assembly bearings, the oil lubricates gear transmissions of the assembly drive. The total power delivered to the assembly drives is not high (of the order of 200-500 hp), however, due to the relatively small dimensions in weights, the assembly drives represent significantly stressed points and specific attention must be paid to the lubrication requirements. At the same time, the gears of these mechanisms, due to moderate loads and rates of slip, may be reliably lubricated with low-viscosity oils.

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In connection with the uniform and balanced rotation of the engine turbocompressor shaft, the maximum load on the roller and ball bearings of a subsonic TRD usually does not exceed 1300-1500 kg (in piston engines the crankshaft main bearing load may reach 10,000 kg). This permits us to provide reliable lubrication of AGTD bearings with oils which withstand a critical oil film destructive load (P_k on a four-ball machine) of the order of 35-45 kg, whereas oils employed, for example, for the lubrication of aviation piston engines (MK-22, MS-20), have values of 70-80 kg. However, in connection with tendencies toward increasing the operating temperatures of oils in the supersonic TRD, it is advantageous to increase this indicator for low-viscosity oils by means of introducing special additives.

The oil system in the AGTD is isolated from the zone of burning fuel, which fundamentally distinguishes it from the oil system of internal combustion piston engines. Therefore lubricating oil losses in the AGTD are not observed, and the consumption, which is not significant, amounts to on the average 0.25 to 1.5 kg/hr. Oil consumption in the AGTD is considered to be nonreturning losses, which are composed of oil losses through the labvrinth seals, oil thrown off through the breather system, disintegration and conversion into products of intensive oxidation under the influence of high temperatures. A certain amount of the lubricating oil is vaporized, which causes it to be released into the atmosphere through the breather system.

Since the power expended in overcoming friction in turbocompressor anti-friction bearings is not high, large quantities of heat are not generated in these bearings, which usually occurs in the bushings of sliding bearings. However, in a power-boosted TRD, the bearings are heated significantly, which requires their intensive cooling. Since the oil system capacity of a TRD is usually not great (from 7 to 25 l), the pumping of oil through the engine must be quite intensive for sufficient heat removal from hot engine parts.

The required rate of oil flow to the engine is determined by the amount of heat which must be removed; this rate is made up of the oil flow through the turbine rotor bearings, the assembly drives, the TVD and also through the reducer. The rate of oil flow through the turbocompressor rotor bearings depends on the load on them and on the number of revolutions, and is on the average (in l/hr):

- 20 -

for compressor roller bearings	120-160
for compressor ball bearings	210-270
for turbine roller bearings	300-380

The rate at which the oil is pumped through the housing of the assembly drives and through the reducer is determined by the power transmitted to the oil, the efficiency and, just as in the case of pumping oil through the bearings, by the thermal capacity of the oil and the maximum permissible temperature of heating in the process of passing through the engine.

With a TRD oil system capacity of 15 ℓ, for example, the rate at which oil is pumped through the engine under various operating conditions may be 900-950 ℓ/hr. Here one cycle of pumping all the oil through the engine is accomplished usually in 0.5-1 min; oil velocity in the channels and pipelines of the evacuation line is 0.3-1 m/sec, and in the pressure line from 1.5 to 3 m/sec.

The temperature operating conditions for lubricating oil in TRD bearings are different. As a rule the lowest operating temperature is observed at the front compressor bearing, and the highest temperature at the turbine bearing. Thus the compressor bearings in a subsonic TRD are heated during operation to 100-130°C, and the turbine earing to 160°C[1].

The operating temperatures of subsonic TRO bearings which are in contact with oil are shown in Table 1, and oil temperatures at the output of the bearings are shown in Table 2.

In the supersonic TRD the loads on the friction points increase, and in this connection the temperature operating conditions of the lubricating oil are more severe (Tables 3 and 4).

The turbine bearing temperature increases sharply after the engine is stopped (see Table 1), when the oil flow and air cooling of the bearing cease, and heat from the turbine vane continues to be applied. The curve of increased temperature of the turbine bearing after the engine is stopped is shown in Figure 14 [4].

The temperature operating conditions for lubricating oil in the TVD as a function of design and engine power are shown in Table 5.

Table 1. Subsonic TRD Friction Point Temperatures

Friction point	Bearing temperature °C	
	During engine operation	With engines stopped
Reducer rpm	80–110	80–110
Compressor bearings		
Front	50–80	50–80
Rear	100–125	125–150
Turbine bearings	125–150	240–260

Table 2. Subsonic TRD Oil Temperature at the Bearing Output

Turbine speed, rpm	Output oil temperature °C		
	From the front compressor bearing	From the rear compressor bearing	From turbine bearing
12,000	32–38	57–72	71–88
18,000	43–60	88–113	85–123

Table 3. Supersonic TRD Thermal and Mechanical Loads on
Friction Points*

Points	Maximum Temperature °C	Load, kg
Bearing		
Front support*	100	5,000
Central support*	120	3,000
Rear support	200	4,200
Gears		
Central reduction	120	14,700**
Reducer	120	13,800**

* For aircraft with a Mach number of 2-2.5.
** In kg/cm².

Table 4. Oil Temperature Operating Conditions in the Bearings
of Various TRD Turbines

	Engine type		
	Sub-sonic	Sonic	Super-sonic
Temperature, °C			
Turbine bearing	175	175-300	300-400
Oil	90	90-150	150-200
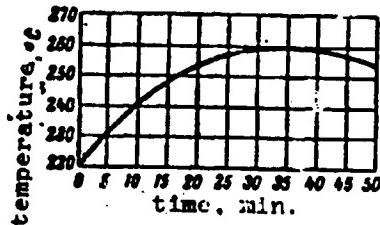
Figure 14. Temperature change curve of the turbine bearing
external ring after stopping the engine

Table 5. Contemporary TVD Lubricating Oil Temperature
Operating Conditions

Indicator	Engine model			
	1	2	3	4
Maximum oil temperature at the engine input, °C	85	80	90	75-85
Maximum oil temperature at the engine output, °C	115	110	115	85-95
Heat absorbed by oil under nomial conditions, kcal/min*	850	1850	850	880-890

*With an engine input oil temperature of 80°C.

In a TVD having a power of the order of 4000 hp at a total oil system capacity of approximately 80 ł, the oil may be heated at the friction points to the following temperatures (in °C):

    rear compressor bearing 130

    turbine bearing 160

    reducer .... 110 - 130

    average oil temperature at the engine input .... 80 - 100

    average oil temperature at the engine output .... 100 - 120

For a TVD of the indicated power we stipulate that the oil temperature at the output of the lubricated points of the engine is 20°C higher than at the input to the engine (i.e., after the fuel-oil radiator), and that the oil

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temperature at the output from the reducer is 8-10% higher than the average temperature of the oil leaving the engine.

Since the bearing temperatures of the engine are not identical, normal cooling of the bearings is achieved by passing various quantities of oil through them. Thus through the thermally stressed turbine bearing, two-three times more oil (to 400 l/hr) is pumped than through the compressor bearing.

Bearing temperatures in the supersonic TRD of the near future will be 450-500°C and higher; this makes the operating conditions for lubricating oil considerably more severe and requires a sharp improvement in resistance to oxidation. Naturally, the more the engine is power boosted and the more power taken from the engine, the higher the temperature of the gas in front of the turbine and the temperature of the bearings and, therefore, the higher the temperature of the lubricating oil. Temperature distribution in friction points of a supersonic TRD is shown in Figure 15 [100].
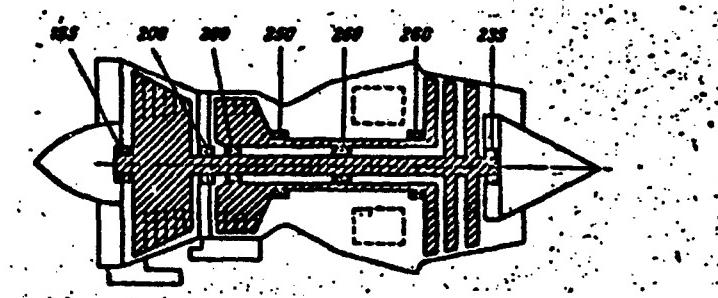
Figure 15. Temperature distribution (in °C) at TRD friction points. Oil temperature at the engine input is 150°C, and 200°C at the output.

The quantity of lubricating oil delivered to the bearings of the engine in the final analysis depends on the bearing loads. Thus in a TRD with axial compressors, 3-6 times more oil is delivered to the stressed bearings than to similar bearings in a TRD with a centrifugal compressor.

Usually the range of operating temperatures of the lubricating oil in the AGTD is accepted as characterized by the average oil temperature at the input and at the output of the engine. It is apparent from this that the average oil temperature at the output of the engine does not in any way

reflect the true temperatures of oil overheating at individual friction points. This must be considered in choosing oil for engines and in evaluating its high-temperature properties.

In engines which have fuel-oil radiators, the oil operates under better conditions, since it is cooled more effectively (to approximately 40-50°C), than in engines without radiators (to 70-80°C).

The temperature operating conditions of lubricating oils in a TRD in recent times have been made especially severe in view of the increase in the flight speeds of supersonic aircraft to Mach 3 and above. As a result of the high air compression and the increase in its pressure at the aircraft exit cone, the temperature of the air entering the engine has increased sharply. The dependence of the temperature of the air which enters the engine on aircraft speed (at an altitude of 11,000 m) is characterized by the following calculated data:

Aircraft speed, km/hr	Airtemperature, °C
subsonic	-55
105	-13
2150	120
3200	more than 300

An increase in the temperature of the air entering the engine causes a sharp increase in the temperature cycle of engine operation; thus the temperature operating conditions of the lubricating oil are more severe.

During supersonic flight speeds the temperature of the aircraft housing increases sharply as a result of air friction, which also negatively influences engine cooling conditions and the cooling of the lubricating oil within the engine. Airframe temperature values of supersonic aircraft, manufactured of steel and titanium, are shown in Figure 16 [100].

In reaching the zone of high temperatures, which includes the bearings and other hot parts, part of the oil vaporizes which facilitates spraying of the oil at the exit of the oil injectors and mixing the oil with air in oil cavities of the gear assembly housings.

Engine oil consumption (usually from 0.25 to 1.5 kg/hr), caused mainly by losses through the breather system, are associated first of all with the vaporization of of low-boiling point fractions. This is confirmed by a

significant increase in viscosity of the oil after extended operation in the engine, notwithstanding the constant addition of fresh oil. Therefore lubricating oils employed in the AGTD must have a uniform fractional composition and minimum volatility. High temperatures and intensive contact with air during the spraying of oil from injectors and during the lubrication of drive assembly gears causes rapid oxidation. In addition, the oil contacts various metals and alloys, many of which are themselves pro-oxidants. Copper, bronze, lead bronze, lead, magnesium, aluminum, steel and other metals and their alloys [16, 17] are the most widely employed metals in AGTD construction. As a result of oil oxidation on engine parts and in the oil system, small, sticky residues and deposits, as well as varnish and abrasive substances of the carbene and carboid type appear, which are products of intensive oxidation of lubricating oil. In order to increase the

period of operation of the lubricating oil without a change and to decrease deposits in the engine, it must be sufficiently resistant to oxidation.

Lubricating oil operating conditions in the AGTD (the high cycle ratio, intensive mixing of oil with air during spraying in the process of lubricating bearings and gears) facilitates its foaming. The oil from bearings, toothed gears and other lubricated points may have as much as 30% by volume of air. In a contemporary TRD the quantity of air entering the oil during oil spraying in the injectors alone may attain a value of 20 ml/kg of oil. In the engine oil tank the pressure is always lower than in the remaining part of the oil system; in addition, it is significantly reduced with an increase in flight altitude which creates conditions for intensified oil foaming.

Intensive oil foaming impairs the operation of the engine oil system. The danger of throwing oil through the breathing aperture of the oil tank arises, which leads to an increase in oil consumption and may cause the cessation of oil delivery to engine friction points. Foaming oil has poor thermal conductivity and reduced heat capacity, and therefore it removes heat from hot engine parts less successfully. The output of pumps which evacuate foaming oil is reduced. Therefore the foaming tendency of oils employed in the AGTD must be minimal.

According to specifications starting of the TRD must be accomplished rapidly and reliably by the starting device in 60-90 sec at temperatures from -40 to -50°C (minimum oil temperatures for extended parking of aircraft

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under north climatic zone conditions). At such low temperatures the oils
employed cannot provide for a normal engine start, and they must be warmed up
by airdrome heating facilities.
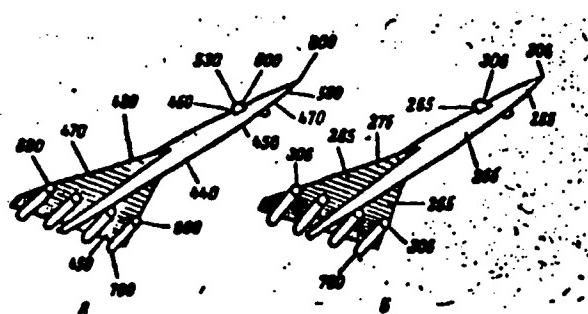
Figure 16. Provisional temperatures (in °C) of the airframes of
supersonic aircraft during flight: A, An airframe of steel and
titanium, at a speed of Mach 3; B, An airframe of aluminum and
titanium (10%), air speed Mach 2.2

Due to the high viscosity of the lubricating oil in a cold engine,
starting of the turbocompressor assembly is not possible, and initiation of
the required starting cycle is hindered. The delivery of oil to the engine
friction points is reduced due to reduced oil pump output, which is connected
with high oil viscosity. The curve on Figure 17 shows the relationship
between the temperature of the oil being pumped through and the output of the
oil pump. The small starting torque of the antifriction bearings facilitates
by far starting of the engine at low temperatures; nevertheless the lubri-
cating oil at low temperatures must have minimum viscosity and good pumping
qualities at the lubrication points. This is particularly required for the
reason that in order to provide for the normal starting process of the AGTD
turbine, the speed of rotation of the turbine must be approximately 1500 rpm,
which is difficult to attain with a turbostarter with the increased resist-
ance of high-viscosity lubricating oil.

Oil Operating Characteristics in the TVD

Some characteristics of lubricating oil operating conditions in the TVD
are due to the presence in these engines of gear reducers. TVD reducers have
a gear ratio of the order of 10:1 and with small dimensions and compact size

must transmit high power, amounting to 17,000-20,000hp. Therefore the reducers have a complex kinematic design, and their gears operate with high loads and speeds. For example the contact shear stress in the toothed reducer gears amounts to approximately 4000-6500 kg/cm^2, and the contact compressive stress amounts to 10,000-11,000 kg/cm^2 [18].
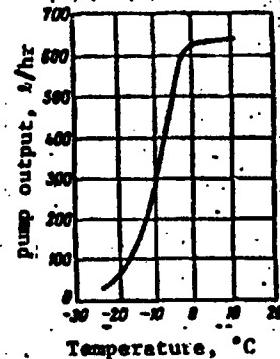
Figure 17. Oil pump output as a function of the temperature of oil being pumped. Oil viscosity at 50°C is 60 cs.

At the high surface stresses generated along the line of engagement of the gear teeth, the lubricating oil which possesses insufficient capability to maintain itself on the metal and to withstand the pressure, will be squeezed from the contact zone which leads to a great amount of wear, jamming or breakage of the gear teeth. Therefore the lubricating oil employed in the TVD reducer must have high load carrying capacity and good lubricating properties. More often than not these properties are characteristic of high-viscosity oils, however the use of such oils in the TVD is not advantageous due to the use of a single system of lubrication for the turbocompressor and reducer. A low-viscosity oil is required for quick and easy starting of the engine turbine, and a high-viscosity oil with increased lubricating proper-ties is required for lubrication of the highly stressed reducer gears. These contradictory requirements create serious difficulties in the development of qualified TVD oils. It is for this reason that special lubricating oils are employed in the TVD which differ in operating properties from the TRD oils [19, 20].

A significant property of the reducer is the requirement to deliver to it an abundant quantity of oil, since the amount of heat which must be

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removed from the reducer is quite large. The quantity of heat absorbed by the lubricating oil in the reducer may be determined in the following manner. In the TVD approximately 10% of the power is expended in the form of reactive thrust through the reaction nozzle, but 90% of the power goes to the reducer for the drive to rotate the airscrews. With a TVD power of 4000 hp, the reducer will transmit a power of 3600 hp; with an efficiency factor of 0.98 the power losses in the reducer amount to 72 hp, which is equivalent to 080 kcal/hr of heat. A certain part of this heat will be lost through the reducer housing, but the main part of the heat must be removed by the lubricating oil.

With an engine power of 11,000-12,000 hp, heat removal by the oil in the reducer will be approximately 2000 kcal/hr. In order to remove such a large quantity of heat from the reducer, the flow of oil through the TVD is increased. In the AI-20 engine under nominal conditions, the oil flow attains a value of 135 kg/hr, and in more powerful engines, the value is 1900 kg/hr.

TVD lubricating oil with a high load-carrying capacity, good starting properties and sufficient thermal oxidation stability may be developed not only on the basis of petroleum, but also of synthetic raw material with the simultaneous employment of complex and effective additives [21, 22].

Oil Quality Requirements

The type of lubricating oil employed in an engine is determined by design characteristics and specifications of the engine, mainly by the loads on rubbing parts and points, by their operating temperatu and types of bearings.

Lubrication Capability

One of the basic requirements for subsonic ACTD oils is the reliable lubrication of parts within a temperature range of ~50 to 150°C. For a supersonic thermally stressed TRD, the upper limit must be higher. The oil must provide for minimum wear of parts (first of all of the turbocompressor bearings) not only during ordinary operating conditions, but also during short-term disruptions of the liquid lubrication cycle. Usually such a disruption occurs during engine starting after an extended period of standing and especially under low temperature conditions when insufficient oil arrives at friction points.

Experience in the application of TRD petroleum and synthetic oils in the USSR and abroad reveals that oil satisfies engine requirements insofar as anti-wear properties are concerned with a minimum critical load value for oil film breakdown (value P_k, determined on a four-ball friction machine) of 40-50 kg. For TVD oils this indicator must attain a value of 70-90 kg.

Starting Properties

AGTD lubricating oils must be characterized by good starting (low-temperature) properties. These properties are determined by a complex of physicochemical indicators, such as the slope of the viscosity-temperature curve, the viscosity level and to a certain extent the pour point. For AGTD use lubricating oils are preferred with the mildest slope in the viscosity-temperature characteristic, i.e., oils in which the influence of temperature on viscosity change is minimal.

The basic indicator which is important in the process of engine starting at low temperatures is the viscosity level, which characterizes the pumping quality of the oil under these conditions. Bench tests, accomplished at -54°C, have revealed that even during operation with low-viscosity petroleum-based oil, the pressure in the oil system is quickly reduced and after ten minutes of engine operation the pressure drops almost to zero due to a sharp increase in oil viscosity and the reduction in oil pump output.

Oil pumping quality may be characterized by a critical temperature, i.e. by a temperature at which delivery of the oil to friction points is disrupted or ceases altogether. Table 6 shows tentative critical temperatures for the pumping quality of oils of various viscosities.

It is obvious that the critical temperature of disruption or cessation of oil delivery depends on oil viscosity. Foreign TRD exploitation has revealed that normal oil pumping quality is disrupted with a viscosity of approximately 5000 cs and ceases at 20,000 cs. Depending on the starting power of the starting devices for domestic AGTD, the maximum viscosity of the oil which provides a normal engine start without warm-up cannot exceed 2000-4500 cs; this viscosity for low-viscosity petroleum-based oils is observed at temperatures from -30 to -35°C. The viscosity of lubricating oils with optimum starting properties at temperatures from -4u to -50°C must be 2000-4500 cs, with a pour point to -60°C.

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Table 6. Pumping Quality Critical Temperatures for
. TRD Lubricating Oils

Oil	Kinematic viscosity at 50°C	Temperature, °C	
		At which oil delivery is disrupted	At which oil delivery ceases
Petroleum	7	-43	-51
Petroleum	150	-1	-15
Synthetic	7	-51	-59
Synthetic	8	-48	-56

Thermal Oxidation Stability

AGTD lubricating oil must be characterized by the ability to preserve
its initial properties, i.e. must be stable with respect to oxidation during
extended engine operation, and must not form deposits, varnish and other
oxidation products in the engine and must not cause corrosion of metals due
to an increase in acidity.

According to practical data oil in a contemporary TRD in one engine
cycle (beginning at the arrival at the lubrication points and the exit to the
oil radiator) is heated on the average by 40-70°C.

The average operating temperature of the oil in a subsonic TRD usually
does not exceed 120-150°C; in a supersonic TRD this value may be 250°C and
above. Therefore lubricating oil for a subsonic TRD must be stable to
140-160°C, and for a supersonic TRD, apparently, to a value of the order of
300°C and above.

In connection with the high operating temperatures in the supersonic TRD
abroad, significant difficulties were experienced in development of thermally
stable oils for these engines [23]. Thus the development of the supersonic
transport aircraft "Concord" (an Anglo-French company) has been retarded due
to the lack of the required materials, not the least of which has been the

lubricating oil. In engines of the "Bristol Siddley" firm, the oil
temperature is 120-130°C, and in the engine of the supersonic aircraft
"Concord," it must increase on the average to 180°C. From several lubrica-
tion points in this engine the oil will enter the pumping system heated to a
temperature of 285°C, and will come into contact with air having a temper-
ature up to 350°C. The question is being discussed in many foreign refer-
ences [24-28] concerning the characteristics that must be possessed by oils
intended for supersonic transport aircraft with a flight speed of Mach 2.2
and above. Here most attention is being devoted to the requirements for
thermal oxidation stability of oils and to a study of organic and other
compounds which may be used as a basis for high-temperature lubricating oils.

This question will be examined in detail in Chapter Thirteen.

Stability of Fractional Composition and Other Properties

AGTD petroleum-based lubricating oil must be uniform and have a stable
fractional composition; this causes minimal volatility of low boiling point
fractions, as a result of which oil consumption is reduced and the viscosity
properties of the oil are maintained during the entire service period of the
oil in the engine. Therefore the requirement for minimum volatility and
possibly narrow fractional composition (boiling away within the limits
60-70°C in place of the usual 100-120°C) is quite essential for oils of
petroleum origin; for synthetic oils this is a very important requirement.

In conclusion it is necessary to point out that AGTD oils must display
minimum foaming, must have a high flash point and self-ignition point and
must not destroy metals, rubber and various other sealing materials and
coverings. The oil must not be toxic in the liquid form, in vapors and in
mixtures with air.

An effort should also be made for the cost reduction of lubricating
oils; however, this factor is not a decisive one, for the high quality of
oils gives a greater economic effect as a result of oil operation without
changes and an increase in the life of the engine.

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Footnotes

1. To p.21. The temperatures of bearings, fraction points and oil temper-
   atures presented here and subsequently were taken from various sources
   and for various models of engines; therefore they differ somewhat among
   themselves and are not always fully comparable. Nevertheless these data
   are of definite interest since they characterize the overall picture of
   of lubricating oil operating conditions.

CHAPTER THREE

DOMESTIC TRD LUBRICATING OILS

The Selection, Manufacturing Methods and Basic Properties

Low-viscosity lubricating oils, obtained from a petroleum base, are
widely employed in the Soviet Union. These oils have viscosities of 6-9 cs
at 50 °C and operate satisfactorily in subsonic TRD installations with
moderate thermal conditions.

It may be assumed that in the USSR petroleum TRD and TVD lubricants
will not soon lo`e their significance.

A short examination of the history of the development and application of
petroleum lubricants for the TRD in the Soviet Union may be of interest. In
the period of the formation of domestic jet aviation (1947), there were no
special TRD-qualified oils. Tests and final adjustment of the engines were
accomplished using oils intended for other types of technology, and these
oils, which in viscosity and lubricating properties gave satisfactory
results, were assumed to be applicable to the TRD. These included trans-
former, AU spindle oil, L turbine oil and mixtures of other aviation oils,
including MS-14, MS-20 or MK-22 with transformer oil. To the transformer oil
was added 0.05-0.1% stearic acid in order to improve its lubricating proper-
ties. Both the oils and the mixtures differed sharply in low-temperature
properties, thermal oxidation stability and other properties, which created
difficulties in TRD exploitation. Due to viscosity fluctuations at low
temperatures for individual batches of the same oil and of their mixtures,
the temperature ranges for engine starting in winter were not identical. In
evaluating the possibility of employing a specific oil in the TRD, the basic
criterion accepted was the viscosity which provided for reliable engine
starting without employing airdrome warm-up facilities. This criterion is
still one of the basic criteria today.

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In order to maintain equipment readiness in the aircraft park, the oil must provide for reliable engine starting in an optimum case down to an ambient air temperature of -50°C.

The following measures were taken in connection with the lack of special low pour point oils in the 1945-1947 period:

thinning of the oil with aviation gasoline before starting the engine;

use in place of oil in the TRD of synthetic products with a low pour point;

use in engines of the lowest viscosity petroleum oils.

For a long time 10-15% of T-1 fuel was poured into the oil system of the engine before stopping; this was accomplished in agreement with instructions for engine use, but created technical difficulties, caused increased engine wear, and did not solve the problem.

From a number of synthetic products available at the time, several silicones (polysilicone) were tested for TRD use; these compounds were characterized by a very mild slope in the viscosity-temperature curve and a pour point of approximately -60°C. The test revealed that the basic shortcomings of polysilicone liquids are the insufficient lubricating capability and the tendency toward the formation of jellies at increased temperatures. These shortcomings and also the high cost of polysilicones and their shortage did not permit using them as TRD lubricants.

Petroleum Oils and Their Preparation

Low-viscosity petroleum oils were acknowledged to be the most promising oils with satisfactory starting characteristics. In particular, transformer oil (GOST [All-Union State Standard] 982-56) had the lowest viscosity of all the oils employed and had a low pour point. Stearic acid was added to the oil at the airdromes, which created significant difficulties in oil storage and use. Work based on the requirement to introduce stearic acid into the oil was checked on instruments which reproduced sliding friction; therefore conclusions concerning the poor lubricating properties of the transformer oil had to be checked. It was also necessary to check established transformer oil change periods in various engines with similar temperature operating conditions.

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Special tests accomplished with a TRD revealed that in these engines it is possible to employ low-viscosity petroleum oils without stearic acid; for all domestic TRD installations petroleum oil is suitable, i.e. transformer oil under the condition that the oil be changed after each 100 hr of engine operation. Then petroleum oil of a special type was tested and authorized for use in the TRD; the MK-8 (GOST 6457-66) type, which differed from transformer oil by better low-temperature properties and by a stricter selection of the petroleum base used in its production.

Notwithstanding its significant shortcomings, the MK-8 oil has been used for many years in conjunction with transformer oil as the basic type of petroleum lubricant for the subsonic TRD. Since the MK-8 oil did not fully satisfy requirements in engine starting properties, antioxidation properties and stability of fractional composition during extended operation in the TRD, in the period 1959-1963 improved petroleum oils were developed for the domestic subsonic TRD: these were the MK-6 (GOST 10328-63) and the MS-6 (GOST 11552-65) oils. They are characterized by a narrow fractional composition, a somewhat lower initial viscosity (6 cs at 50°C in comparison with 8 cs for MK-8 oil), by good starting characteristics and a stable fractional composition.

In a TRD with an increased temperature cycle, MK-8p (FOST 6457-66) oil is employed, which in comparison with MK-8 oil has somewhat improved thermal oxidation stability. It is prepared by introducing into MK-8 oil 0.6% by weight of the antioxidizing additive dibutyl paracresol of the DBK-69 brand, known under the name of "Ionol."

The following petroleum oils are used at the present time for the lubrication of domestic TRD installations: MK-8 and MK-8p (GOST 6457-66); transformer oil (GOST 982-518); MK-6 (GOST 10328-63); MS-6 (GOST 11552-65).

In comparison with MK-8, transformer oil has poorer low-temperature characteristics, and its application at the present time is not significant. The MK-6 and MS-6 oils, insofar as exploitation characteristics are concerned, are quite close to each other, are interchangeable and in essence represent the same type of oil prepared from petroleum of different sources.

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The Preparation of MK-8 Oil

Due to the strict requirements established for the low-temperature properties and thermal oxidation stability of TRD domestic petroleum oils, until recent times their production has involved selected crude. Thus, low MK-8 pour point oil is manufactured from oil distillates of selected Baku crude, in particular from high-quality nonparaffinaceous Balakhany crude oil. However, in connection with the tendency to reduce the extraction of Balakhany crude, obtaining TRD oils for widespread use from this crude is no longer promising. According to GOST 6457-66, the adding of 14% Romanovka crude is authorized during the preparation of MK-8 oil; the oil may also be prepared from Dossor crude. In this case somewhat poorer viscosity-temperature and antioxidation oil properties are authorized.

The MK-8 oil is obtained by means of cleaning the distillates with sulfuric acid (9%). Transformer oil is prepared using the same technique from a mixture of other Baku crude oils, including Balakhany, Romanovka, etc. taken in various ratios (Table 7).

The method of obtaining TRD oils by narrowing the fractional composition is quite promising. This method permits the manufacture of oils which satisfy the requirements of GOST 6457-66 from a number of domestic crudes, which were not previously employed for this purpose.

In addition, MK-6 and MS-6 oils obtained by this method have significantly better exploitation characteristics in comparison with the MK-8 oil.

The fractional composition of the MK-8 oil changes in the process of its operation in an engine. This is associated with vaporization from the oil of the low-boiling fractions, as a result of which oil viscosity rises considerably. Thus investigations have revealed that this is caused by the broad fractional composition of the oil, i.e. it boils away in a wide range of temperatures (on the average from 270 to 440°C). The vacuum distillation curves of the MK-8 oils are shown in Figure 18. It is apparent from the drawing that the MK-8 oil contains a significant quantity of low-boiling fractions; their vaporization in the engine at increased temperatures causes a sharp rise in the viscosity of the oil as a result of the particularly high-viscosity heavy fractions contained in the oil. It follows from this that TRD lubricating oils must have a more uniform composition, i.e., they must not contain low-boiling and high-viscosity heavy fractions. Then with

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partial oil vaporization, a change in oil viscosity will be less significant. Other properties of oils with a narrow fractional composition will also display less change during their partial vaporization; therefore oils of this type may operate for an extended period of time in the TRD with no significant changes in the viscosity-temperature and other properties.

Table 7. The Crude Petroleum and the Technique Used in Preparing TRD Petroleum Oils

Oil	Crude petroleum	Distillate	Distillate cleansing
MK-8	light Balakhany crude, with permissible addition of 14% Romanovka; and Dossor crude	oil distillate 300-400°C	acid-contact
MK-8p*	light Balakhany crude, with permissible addition of 14% Romanovka; and Dossor crude	oil distillate 300-400°C	acid-contact
trans-former oil	mixture of Baku crudes in various ratios (Balakhany, Romanovka, Buzovna)	oil distillate 300-400°C	acid contact
MK-6	Troitsko-Anastas'yevka oil of IV level of Krasnodar Kray deposit	oil distillate of narrow fractional composition 320-370°C	acid
MS-6**	Tuymazy Devonian petroleum of the eastern deposit	oil distillate of narrow fractional composition 300-370°C	selective, with phenol; intensive dewaxing

* The oil contains 0.6% antioxidaticn additive Ionol.
** The oil contains 0.2% antioxidation additive Ionol.

The Preparation of Oils of Narrow Fractional Composition

Work has been accomplished in the selection of the optimum fractional composition for MK-6 and MS-6 oils. The method of selection consisted of the following: oil distillates were prepared under laboratory conditions in a vacuum for narrow fractions and after studies of the viscous properties of these fractions, mixtures were prepared satisfying the requirements for minimum volatility and possessing a mildly sloping viscosity-temperature curve. In preparing oils of narrow fractional composition it is most advantageous to employ the maximum possible number of initial distillation fractions.

In order to obtain oils of narrow fractional composition, oil refineries employ devices for precise rectification of oil fractions [29, 30].
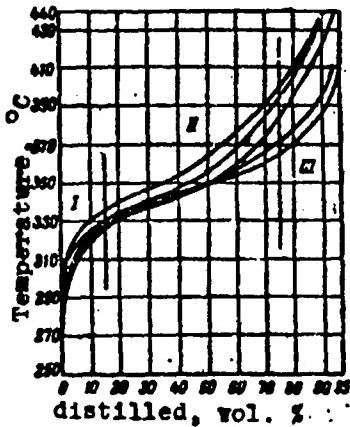
Figure 18. The fractional composition of different specimens of
MK-8 oil: 1, Low-boiling fraction; 2, Medium fractions;
3, High-viscosity heavy fractions

MK-6 oil. This oil is prepared by means of sulfuric acid cleaning of an
oil distillate of narrow fractional composition, obtained from Troitsko-
Anastas'yevka crude of the IV level of the Krasnodar Kray deposit. This
crude has high quality and is nonparaffinaceous, nonsour and is highly
aromatized (it contains up to 40% of aromatic hydrocarbons) with a low pour
point. The lack of paraffins permits obtaining from this crude without
dewaxing low pour point oils of the transformer, capacitor and other types
[31].

The properties of the MK-6 oil obtained from this crude are embodied
in the selection of a distillate of specified fractional composition,
which determines the optimum low-temperature properties and the lowest
volatility of the oil, and also by the selection of the cleaning depth of the
distillate by sulfuric acid. With deeper sulfuric acid cleaning, the
viscosity-temperature characteristics of the MK-6 oil is improved as a
result of the removal of aromatic hydrocarbons, but oxidation stability
falls. Investigations have revealed [32] that in order to obtain MK-6 oils
with optimum properties, their fractional composition must be within the
range 320-370°C, and cleaning must be accomplished with a 6% quantity of 96%
sulfuric acid.

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MS-6 oil. This oil is obtained from sour Tuymazy crude from the eastern
deposit. Notwithstanding the high content in eastern crude oils of paraffin
hydrocarbons and sulfur content, they may be employed for the manufacture of
low-viscosity low pour point oils. The MS-6 oil is obtained by means of
solvent treating of the distillate with phenol (the ratio of phenol to crude
is 2:1) with subsequent deep dewaxing of the raffinate obtained in an
acetone-toluene solution with a final cooling temperature of -65°C [33, 34].
Further, the oil is subjected to secondary rectification with the aim of
narrowing the fractional composition. The optimal fractional composition of
the MS-6 oil is established as 300-370°C. In order to improve the thermal
oxidation stability in the MS-6 oil, 0.2% antioxidation additive Ionol is
introduced.

It should be noted that only by narrowing the fractional composition of
the distillate of Tuymazy crude are we successful in obtaining an oil with a
pour point of -55 to -57°C for acetone-toluene solution dewaxing. In the
case of the usual fractional composition (300-400°C), oil with a pour point
of -55°C may be obtained only with the use of scarce methylethyl ketone.
Thus narrowing of the fractional composition permits us to draw into the
production of TRD oils the broad resources of eastern crude. The basic
properties of petroleum-based TRD lubricants are shown in Table 8.

The MK-6 and MS-6 oils in comparison with the MK-8 oil possesses better
operating properties, including lower viscosity at -40°C, a smoother
viscosity-temperature curve and a lower pour point.

Type MK-8 oils. Recently investigations have been conducted in the USSR
in connection with the possibility of obtaining low pour point oils of the
MK-8 type from domestic crude oils previously not employed for these
purposes. In 1958 at the AzNII NP [35] [Azerbaydzhan Scientific Research
Institute for Petroleum Processing] the MK-8 oil of narrow fractional
composition was obtained from a mixture of Balakhany and Romanovka crude oils
by means of acid-contact cleansing of narrow fractional composition compounds
(60-70°C), separated by secondary distillation of MK-8 prepared commercial
oil or its distillate. In both cases the oil displayed insufficient oxida-
tion stability. This may have been caused by the removal from the product in
the process of secondary rectification of natural antioxidant agents, which
remained in the heavier fractions of the distillate.

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Table 8. Basic Physicochemical Properties of Domestic TRD Petroleum Oils

Indicator	OIL				
	MK-8 (GOST 6457-66)	MK-8p (GOST 6457-66)	Transformer (982-56)	ЧK-6 (10328-63)	MS-6 (GOST 11552-65)
Kinematic viscosity, cs					
at 50°C	Min 8.3	min 8.3	max 9.6	6.0-6.3	6.0-6.3
at 20°C, maximum	30	30	37.3	19	18
at -40°C, maximum	Approx. 8500	–	–	3300	1700
Kinematic viscosity ratio at -20°C and 50°C, maximum	60	60	–	46.5	30*
Acid No., mg KOH/g, maximum ...	0.04	0.04	0.05	0.04	-.04
Kinematic viscosity at -40°C after evaporation (in accordance with GOST 10306-62) for 2 hr at 150°C; air delivery rate 1.5 ℓ/min and residual pressure 198 mm Hg, cs, maximum.........	–	–	–	5600	not established, determination is required
Stability after oxidation ** quantity of deposits, % max.	0.1	0.15	–	0.1	not available
Acid No. mg KOH/g, maximum ...	0.35	0.60	0.35	0.35	0.15
Ash content, % maximum	0.05	.05	0.05	0.05	0.005
Contents					
sulfur, % maximum	0.14	0.14	–	0.14	0.7
water-soluble acid and alkali		not available			
mechanical impurities					
water					
Temperature, $^\circ$C					
flash point, determined in a closed crucible, minimum.....	135	135	135	140	140
pour point, maximum	-55	-55	-45	-60	-55
Alkali test with acidification points, maximum...............	2	2	–	2	–
Aniline point, $^\circ$C minimum	79	79	–	60	80
Corrosion on C1 or C2 type lead plates (in accordance with GOST 3778-56), g/m², maximum	–	–	–	30	5
Density at 20°C, g/cm³, maximum	0.885	0.885	–	0.90	0.860

* According to statistical data.
** The stability of the MK-8p oil is determined in accordance with a strict method in the VTI [expansion of this abbreviation unknown] in accordance with GOST 981-55 at 175°C and with a rate of air delivery to the tube of 3 ℓ/hr.

The authors have noted [35] that during mazut distillation for narrow fractions with subsequent acid-contact cleaning, it is possible to obtain oils which comply with the thermal oxidation stability requirements of GOST 6457-66. The quality of the MK-8 oil and all of the samples described below is shown in Appendix 1.

According to data from other investigators [32], the thermal oxidation stability of the oil does not noticeably decrease after the secondary distillation. Thus MK-6 oil of narrow fractional composition (325-375°C), obtained by distillation of MK-8 oil (270-420°C) from Balakhany petroleum oil in a secondary rectification device, contains approximately 50% of the initial MK-8 oil; in pour point, smoothness of the viscosity-temperature curve and other properties MK-6 oil surpassed the initial MK-8 oil and in thermal oxidation stability satisfied the requirements of GOST 6457-66.

MS-6 oil is obtained from Kazakh and Shakopovo crude [36] by means of cleaning of the distillate (290-360°C) having a viscosity of 50°C of 5.6-6.1 cs with phenol (from 80 to 300% by weight of the source material), by dewaxing in an acetone-toluene solution with a filtration temperature of -60°C and a final contact cleaning with 7% Sarny earth. After a secondary distillation with the aim of narrowing the fractional composition and the introduction of 0.15% of Tonol, an oil is obtained which satisfies the requirements of GOST 11552-65.

In order to study the possibility of obtaining type MK-8 oil from Anastas'yevka crude, in the laboratories of several petroleum refineries MK-8 oil distillates from the same crude were cleaned with different quantities of sulfuric ac   ith the aim of clarifying the influence of deep cleaning of the oil on its low-temperature and antioxidant properties [31]. The results were that with the usual level of cleaning of the distillates with 6-10% of sulfuric acid with a strength of 94-98%, it was not possible to obtain a standard oil, since after such a cleaning the oil was characterized by a high viscosity ratio at -20°C and 50°C, by increased density, and a low aniline point. In addition, the oil had high viscosity at -40°C (Table 9), which deteriorated the starting characteristics.

Under deep cleaning conditions using 50% sulfuric acid, all of the indicators enumerated correspond to the requirements of GOST 6457-53, except for oxidation stability, which deteriorates noticeably in proportion to the

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depth of the oil cleaning. However, with the introduction of 0.2% of Ionol, stability of the oil reaches the level of MK-8 oil.

Table 9. The dependence of the Physicochemical Properties of MK-8 Oil, Obtained from Anastas'yevka Crude, on the Depth of Sulfuric Acid Cleaning

Indicator	Sulfuric acid content, %				
	MK-8 oil requirements according to GOST 64 -66	6.4	10.0	6.4 + 24% oleum	50
Kinematic viscosity, cs					
at 50°C	min.8.3	8.7	8.7	8.t	8.7
at 20°C	max.30.0	29.3	28.4	28.0	28.5
at -40°C	-	12700	8700	4480	5900
Kinematic viscosity ratio at					
-20°C and 50° C	max.60.0	73.2	72.5	62.3	59.3
VTI stability ..					
deposits after oxidation,%	max. 0.1	0.5	0.12	0.10	0.08
acid no., mg KOH/g	max.0.35	0.20	0.52	0.21	1.20
Pour point, °C	max.-55	-55	-57	-57	-60
Density at 20°C, g/cm ....max	0.885	0.895	0.889	0.884	0.884

Test oils of the MK-8 (MS-8 and MS-6) type may also be obtained from distillates of Anastas'yevka crude (at 300-390 and 300-380°C, respectively) by means of solvent treating these with 70-90% of furfural and subsequent final cleaning of the raffinates with 2% of sulfuric acid and 10% bleaching earth [37]. MS-8 and MS-6 oils obtained are stable without the intrduction of antioxidant additives.

Tests have revealed [38] that MK-8 oil can also be obtained from Zhirnovsk crude in accordance with the following variations in the technical processing methods:

1) dewaxing of the distillate of narrow fractional composition (350-375°C) having a viscosity (at 50°C) of 8 cs with crystal carbamide (100% of the base) in the presence of a methanol activator and subsequent cleaning with 10% sulfuric acid;

2) dewaxing of the distillate of broad fractional composition (300-380°C) having a viscosity (at 50"C) of 5.7 cs is accomplished with crystal carbamide.

In order to raise the viscosity and to reduce the pour point, 1% polymethylcrylate or 0.5% polymethylcrylate and polyisobutylene are introduced into the oil.

MK-8 oil may be obtained from heavy Malgobek [38] by dewaxing a distillate of narrow fractional composition (320-380°C) with crystal carbamide and cleaning with 2.5% sulfuric acid.

This short summary in the methods of obtaining petroleum oils for TRD applications reveals that type MK-8 oils may be obtained from various domestic crudes by means of selecting oil distillates of optimum fractional composition and by their deep cleaning with sulfuric acid, by solvent or carbamide cleaning, or by a combination of- these methods.

MK-8p oil. In a TRD, where the oil temperature at the engine input and output attains values of the order of 120 and 150°C, respectively, MK-8 oil, just as other distillate oils without additives, shows intense oxidation. Since the deposit of intensive oxidation products interferes with engine operation, the necessity arose to improve the thermal oxidation stability of MK-8 oil.

The oxidation stability of MK-8 oil may be improved by the introduction into the oil of the antioxidant additive Ionol. Of the laboratory methods of evaluating the thermal oxidation stability of TRD petroleum oils, the one most clearly reflecting operating conditions in an engine is the method of intensive oxidation in the VTI device, in which the oil is oxidized for 10 hr at 175°C. Into each test tube air is delivered at the rate of 3 ℓ/hr; copper and steel balls serve as oxidation catalysts.

Tests made in accordance with this method of the MK-8 oil, both in its pure form and with the addition of Ionol, reveal that Ionol is a sufficiently effective antioxidant additive; with its introduction into the oil in a quantity of 0.6% by weight, the acid number after oxidation becomes two-three times less, and the deposits four-five times less than without the additive. Thus for an oil specimen having after oxidation an acid number of

1.58 mg KOH/g and 1.34% of formed deposits, after introduction of 0.6% Ionol these indicators were reduced to 0.12 mg KOH/g and 0.04%, respectively.

Different commercial batches of MK-8 oil have different Ionol susceptibilities, but on the average the introduction of 0.6% Ionol into the oil gives a noticeable antioxidant effect (Table 10).

Table 10. The Influence of Ionol on the Thermal Oxidation Stability of MK-8 Oil

Commercial batches of MK-8 oil	Thermal oxidation stability			
	Acid No., mg KOH/g		Quantity of deposits % by weight	
	no additive	With 0.6% Ionol	no additive	With 0.6% Ionol
1	0.93	0.50	1.08	0.28
2	0.83	0.19	0.87	0.02
3	0.75	0.42	1.00	0.10
4	1.67	0.30	1.58	0.05
5	0.87	0.18	0.82	0.03

The results of laboratory tests of the MK-8 oil with 0.6% Ionol were confirmed during engine tests, and this oil began to be employed for thermally stressed TRD installations. Subsequently this oil was designated as MK-8p.

In order to mix the MK-8 oil with Ionol a 10% Ionol concentrate in oil is prepared first at a temperature of 70-80°C and the mixture is agitated. Then the concentrate is dissolved in oil. The prepared oil is filtered.

It is possible to obtain lubricants which are more oxidation resistant than MK-8 and other petroleum oils by the introduction of a complex of thickening, anti-wear and antioxidant additives into a well-cleaned petroleum base of the MK-8 type. The application in thermally stressed TRD installations of such lubricants must be quite promising.

Synthetic Oils

Esters of mono- and dicarboxylic acids have been well studied abroad as synthetic lubricating materials [39-43] and have been employed in those cases when petroleum oils have not provided reliable lubrication for aviation gas turbine engines.

Production

The use of synthetic lubricants has begun in the USSR in recent years [44]. The first experimental-industrial installation for the production of synthetic lubricants on the basis of esters of carboxylic acids was created in 1961 [45].

Esters are obtained by the interaction of acids and alcohols under atmospheric pressure within the temperature range of 140-225°C and in the presence of zinc oxide as a catalyst. Sulfuric and other acids may also be employed as catalysts. In the Soviet Union pentaerythritol esters of synthetic fatty acids with the number of carbon atoms C_5-C_6 are produced [39] in the presence of zinc oxide. Since this process of esterification is cumbersome and is not without technical shortcomings, in order to obtain esters of the acids and alcohols indicated, an improved process [39-40] was suggested in which zinc oxide was replaced with ion exchange resins -- cation exchange resins of a sulfonated copolymer of styrene and divinylbenzene (KU-2 and AV-17 exchange resins). According to foreign references [46], cation exchange resins have long been employed for this purpose.

Mono- and dicarboxylic acid esters with monatomic or multiatomic alcohols have good qualitative characteristics, and di-2-ethylhexyl ester of sebacic acid as a base for synthetic lubricating oil in comparison with esters of other double-base acids has optimum viscosity-temperature properties [39].

The introduction into dicarboxylic acid esters and pentaerythritol esters (or in a mixture of these with diethylhexyl esters) of antioxidant, anti-wear and other additives results in obtaining synthetic oils of types 1 and 2, the properties of which are shown in Tables 11 [47] and 12 [48], respectively. Depending on oil composition, type 2 may be a single or two-component oil.

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Table 11. The Physicochemical Properties of Type 1 Synthetic Oils, Prepared on a Diester Base

Indicator	Requirements of MRTU [Interrepublic Technical Specifications] 38-1-164-65	Test Results	
		Specimen 1	Specimen 2
Kinematic viscosity, cs			
at 100°C, minimum	3.2	3.29	3.30
at -40°C, maximum	2000	1646	1640
at -54°~, "	.1000	8770	9200
Temperature, °C			
pour point, maximum	-60	-	-60
flash point in an open crucible, min	204	212	214
Acid No., mg KOH/g, maximum	.22	0.14	0.13
Oxidation stability at 175°C after 72 hr			
viscosity change at 100°C, % maximum	10.0	9.0	9.3
corrosion of steel, aluminum, magnesium alloy, silver and copper plates, g/m², maximum	±0.2	-	-
viscosity stability at -54°C			
viscosity change after a holding time of 3 hr, %, maximum	6.0	5.9	-
viscosity after holding time of 3 hr cs, maximum	11700	-	11000
Density, g/cm³, maximum	0.926	-	0.921
Saponification No., mg KOH/g, minimum	235	-	-
Ash content, % , maximum	0.04	0.03	p.04
Mechanical impurities,water, water-soluble acids and alkali content	Not Available		

Operating Properties

It has been revealed by investigations that oils based on diesters in all properties (thermal oxidation stability, corrosion properties and change in viscosity) are efficient to approximately 175°C. However, while distinguished by good antioxidant stability in volume, they are not sufficiently stable in a thin film. During oxidation up to 200°C (50 hr) and short-term oxidation up to 250°C (10 hr), these oils maintain a high stability with respect to sedimentation, but already have high acidity. It is significant that the viscosity at -40°C of type 1 oils as a result of their oxidation at 200°C increases sharply (from 1640 to 5250 cs).

Table 12. The Physicochemical Properties of Type 2 Synthetic Oils

Indicator	Two-component oil Requirements MRTU 38-1-164-65	Two-component oil Test Results Specimen 1	Specimen 2	Specimen 3	Two-component oil additive Requirements MRTU 38-1-164-65	Two-component oil additive Test Result	Single component oil Requirements MRTU 38-1-165-65	Single component oil Test Results
Kinematic viscosity, cs								
at 100°C, minimum	3.0	3.6	3,61	3.5	3.5	3.7	5.0	4.8-5.0
at -30°C, maximum	-	-	-	845	-	-	3500	-
at -40°C, maximum	3000	3100	2700	2600	3800	3100	12000	12300
Temperature, °C								
pour point, maximum	-60	-60	-60	-65	-60	-60	-60	-60
flash point in an open crucible, minimum	195	210	215	210	195	210	230	250
Acid No., mg KOH/g prior to addition of antioxidant additive, maximum	0.5	0.5	0.5	0.57	0.5	-	0.5	-
After addition of antioxidant additive, maximum.........	-	-	-	-	4.9-6.0	2.88	4.0-5.5	5.1-5.3
Mechanical impurities, water, water-soluble acids, and alkali content	Not Available							

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Table 12. (continued)

Indicator	Two-component oil				Two-component oil additive		Single component oil	
	Requirements MRTU 38-1-164-65	Test Results			Requirements MRTU 38-1-165-65	Test Results	Requirements MRTU 38-1-165-65	Test Results
		Specimen 1	Specimen 2	Specimen 3				
Stability at 200°C after oxidation for 10 hr quantity of deposits not soluble in isooctane, % max	0.15	0.05	0.04	-	0.7	0.08	0.2	0.3
quantity of deposits not soluble in benzene, % max..	0.03	0.02	-	-	0.05	-	0.03	-
acid no., mg KOH/g, max	1.8	1.6	0.85	0.9	2.0	1.6	2.0	-
Kinematic viscosity, cs at 100°C, maximum	4.3	4	-	-	4.5	-	6.0	-
at -40°C, maximum	-	-	-	-	-	-	-	18500
Corrosion during tests on metallic plates	not available	-	-	-	not available	-	not available	-
Sulfur content, %, maximum ..	-	-	-	-	0.6	-	0.6	-
cokability, %, maximum......	0.3	-	-	-	0.45	-	0.4	-
Density at 20°C, g/cm³	0.980-0.997	0.960	0.985	0.953	0.980-0.997	0.960	0.990-0.997	-
ash content, %								

Not Available

Note. The anti-wear properties of synthetic oils are determined by means of a four-ball machine with balls of ShKh steel with a diameter of 19 mm at a rate of 1500 rpm of the upper ball, for 1 min. The anti-wear property indicators have not been standardized, but a determination is required.

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Based on thermal oxidation stability, the limit of the operating capability of type 1 oils must be considered to be a temperature of not more than 175°C. In quality the domestic type 1 oils comply with the requirements of the American specification MIL-L-7808, and in certain characteristics they surpass the oil of the USA (for example, turboil 15).

Two-component type 2 synthetic oil is sufficiently stable for 50 hr at a temperature up to 200°C and on a short-term basis (10 hr) is stable to 225 and even to 250°C. In this respect it surpasses type 1 oil somewhat. After oxidation at 225°C, the viscosity of type 2 two-component oil at -40°C may increase from 3960 to 12,800 cs, and therefore this oil is efficient only to 175-200°C. After oxidation of oils of this type, they are significantly characterized by the appearance of deposits not soluble in isooctane. In the USA the stability of synthetic oils of this type is not evaluated by deposits, but by several other indicators [49].

In thermal oxidation stability, single-component type 2 oil is close to two-component oil. In the process of operation at increased temperatures, oils of this type are inclined toward the formation of deposits in sump areas of engines and other mechanisms. By introducing antioxidation additives into the oil it is possible to avoid the appearance of these shortcomings and at the same time to improve significantly the anticorrosion properties (Table 13).

Synthetic type 1 oils and two-component type 2 oils have a smoother viscosity-temperature curve than petroleum oils. Single-component type 2 oils possess a higher initial viscosity at 100°C than two-component oils; therefore their viscosity at -40°C attains values of the order of 12,000-12,500 cs. These oils are distinguished by high durability and work well under conditions of high loads on rubbing parts.

Synthetic oils in comparison with petroleum oils have higher anti-wear properties. For example, at 100°C they are characterized by the following critical oil film destructive loads, obtained on a four-ball machine (in kg):

type 1 oil 54
type 2 oil
two-component 54
single-component................. 100
MK-8 petroleum oil 36

Table 13. The Thermal Oxidation Stability and Anticorrosion
Properties of Type 2 Oil Before and After Supplementation
with an Antioxidation Additive

Indicator	Oil with no additive		Oil with additive	
	300°C 10 hr	350°C 5 hr	300°C 10 hr	350° 5 hr
Quantity of deposits, %	0.05	0.145	0.05	0.07
Acidity, mg KOH	0.72	12.18	–	7.28
Corrosion EI-347 steel, g/m^2	-27.5	-30.0	Not available	
AK-4 aluminum	Not available after 3			
Quantity of deposits on the instrument after oxidation ...	low	hr device was clogged	Not available	

The results of investigations reveal that type 2 synthetic oils have the same anti-wear and anti-seize properties at 200°C as MK-8 petroleum oil at 100°C. For type 1 oils obtained on the basis of diesters, the lubricating capability at increased temperatures (155-200°C) drops sharply. Due to the high anti-wear properties and good durability, single-component type 2 oils are successfully employed for the lubrication of heavily stressed gear reducers.

A significant shortcoming of synthetic oils for TRD applications is their corrosive influence on some metals (copper, copper alloys, magnesium alloys, etc.), and also the noticeable disintegration at increased temperatures of gaskets and seals of commercial rubber. Therefore during the use of synthetic oils in TRD installations, it is recommended that metals be protected by means of various anticorrosion coatings and that oil-resistant aviation rubber of special types be employed.

CHAPTER FOUR

THE FRACTIONAL COMPOSITION AND VAPORIZABILITY OF PETROLEUM OILS FOR TURBOJET ENGINES

The Fractional Composition

Such basic characteristics of oils as volatility, vaporizability in the engine, viscosity, low-temperature and other indicators depend on the fractional composition of lubricating oils for TRD applications. During vaporization of the oils, as a result of which the low-boiling fractions are volatilized first of all, the indicated characteristics change.

The more uniform the composition of the lubricating oil, i.e. the narrower the temperature regions in which it is extracted, the smoother will be the viscosity-temperature curve. Therefore if the viscosity curve has any practical significance for lubrication, oils with a more uniform fractional composition must be employed [50]. Individual hydrocarbons or petroleum fractions extracted in an extremely narrow range of temperatures, for example, within the range 3-5°C may serve as an ideal example of a petroleum oil with an absolutely stable fractional composition.

It has already been established [30] that MK-8 oil and also tinnsformer oil from the Balakhany petroleum oil have a wide gractional composition (Table 14).

The distillation of MK-8 oil in a vacuum revealed (see Figure 18) that it consists of up to 15% of low-boiling fractions. During the vaporization of these fractions in the engine, the oil viscosity increases sharply (at -40°C it increases 4-5 times). The fractional composition of several petroleum oils (the boiling point of 5% by volume of the fractions), obtained by means of laboratory distillation with a residual pressure of 2-3 mm Hg, is shown in Table 15.

Table 14. The Fractional Composition of Petroleum Oils
for TRD Application (Average Indicators)

Oil	Boiling limits °C	Boiling range °C
MK-8	260-440	180
Transformer	260-440	180
MK-6	330-380	50
MS-6	305-370	65

Table 15. The Fractional Composition of MK-8 and MS-6 Oils

Fraction number	Boiling point °C MK-8 oil Specimen 1	Boiling point °C MK-8 oil Specimen 2	MS-6 oil	Fraction number	Boiling °C MK-8 oil Specimen 1	Boiling °C MK-8 oil Specimen 2	MS-6 oil
1	203—314	270—317	300—328	11	350—356	355—361	354—355
2	314—324	317—326	328—335	12	356—360	361—368	355—358
3	324—329	326—330	335—341	13	360—368	368—376	359—360
4	329—332	330—334	341—344	14	368—375	376—385	360—352
5	332—335	334—337	344—346	15	375—386	355—394	362—366
6	335—337	337—340	346—348	16	386—395	394—408	366—370
7	337—340	340—343	348—350	17	395—407	408—420	370—375
8	340—343	343—347	350—351	18	407—424	420—440	375—380
9	343—348	347—350	351—353	19 и 20	above 424	above 440	above 380
10	348—350	350—355	353—364				

The selection of the optimum fractional composition of petroleum oils
for TRD applications is achieved in some cases by the inclusion in them of
middle fractions of a distillate of narrow fractional composition; these
fractions have a more smoothly sloping viscosity-temperature curve (for
example, that for MK-6 oil); in other cases this is accomplished by means of
removing from the oil composition the heavy high-viscosity fraction
(MS-6 oil), which also provides the oil with a smoothly sloping viscosity-
temperature curve.

It is apparent from Table 8 (Chapter Three) that MK-6 and MS-6 oils of narrow fractional composition in comparison with MK-8 oil have a significantly smoother viscosity-temperature curve, a lower pour point and after vaporization, their viscosity-temperature properties remain stable.
Figure 19 indicates the improved viscosity properties of oils with a narrow fractional composition.
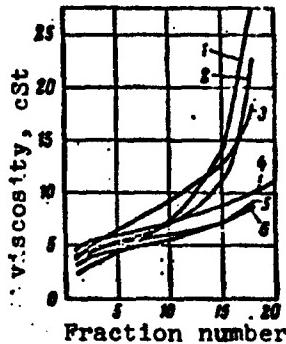
Figure 19. The viscosity-temperature characteristics of petroleum oils of different fractional composition:
Oils of broad fractional composition: 1, Experimental MK-8 oil of Troitsko-Anastas'yevka crude; 2, MK-8 oil from Baku crude; 3, Transformer oil from sour crude. Oils of narrow fractional composition: 4, MK-6 from Anastas'yevka crude; 5, MS-6 from sour crude; 6, MS-6 from Baku crude

The method of narrowing the fractional composition permits us to obtain TRD oils from crude oils which were previously not employed for these purposes (Anastas'yevka, Tuymazy, etc.). The basic advantage of oils of narrow fractional composition is stability in viscosity, low-temperature and other properties after partial vaporization. The initial viscosity of MK-6 and MS-6 oils is somewhat lower than MK-8 oils; however, their lubricating capability in this connection is not reduced.

For synthetic oils, the base of which is composed of individual chemical products or their mixtures, the concept of fractional composition practically loses its significance.

Methods of Determining Fractional Composition

The fractional composition of oils is usually determined by means of their vacuum distillation (a residual pressure of 3-4 mm Hg) in a Klyayzen flask with a dephlegmator. For a more detailed investigation of fractional composition the oil is distilled into fractions comprising 5% by volume,

and distillation curves are plotted with boiling point -- number cf fractions or with boiling point -- viscosity as the coordinates. Fractional composition is also determined by the Bogdanovich vacuum method, which does not fundamentally differ from the method described above.

The vacuum distillation of oils is an operation which is long and rather time-consuming, since establishing the initial boiling point and the end point of the oil is quite difficult. However, it is these very indicators which are quite important ouring plant control over the fractional composition of the oils prepared. The thin-film vaporization method (GOST 8674-58) has significant interest for a comparative evaluation of fractional composition of oils. The vaporization curves of various MK-8 oil fractions (Figure 20 a) obtained by this method are situated on the graph in agreement with their boiling limits during vacuum distillation; they differ significantly from each other in initial boiling point and end point. It is possible to determine rather quickly with this method and with minimum product expenditures the difference in the fractional composition of oils of both petroleum and synthetic origins (Figure 20 b and Table 16).

Table 16. The Fractional Composition of TRD Oils Established By
the Thin-Film Vaporization Method (GOST 8674-58)

Oil	Quantity of vaporized oil, %, at temperatures, °C											
	180	190	200	210	220	240	260	280	300	320	340	360
MS-6	3	9	23	46	83	99	100	—	—	—	—	—
MK-8	4	12	28	48	67	91	97	98	99	—	—	—
MK-6	5	15	31	53	95	100	—	—	—	—	—	—
synthetic oil based on diesters [*]	—	—	1	3	5	11	23	49	95	98	99	99+
synthetic oil based on pentaerythritol esters [*]	—	2	3	8	14	20	36	61	88	93	96	97

[*] The data are obtained as a result of the vaporization of a weight of oil in time.   56
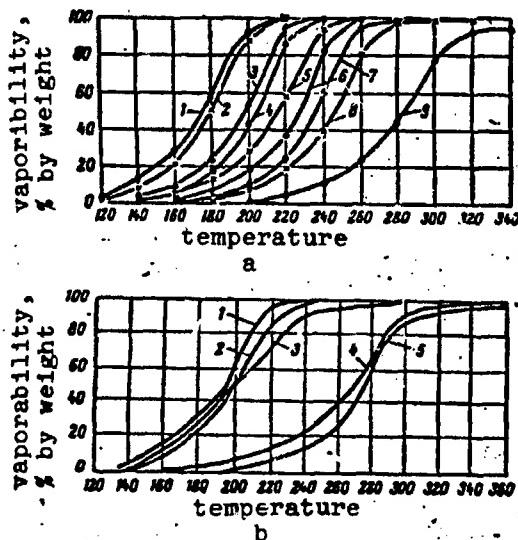
Figure 20. The fractional composition of oils: a, MK-8, deter-
mined by the thin-film vaporization method. The fractions were
obtained by vacuum distillation at the following temperatures
(in °C): 1, 263-324; 2, 324-329; 3, 337-343; 4, 343-350;
5, 350-360; 6, 360-375; 7, 375-395; 8, 375-395; 8, 395-407;
9, 424 and above. b, Various TRD oils obtained by the thin-film
vaporization method: 1, MK-6; 2, MS-6; 3, MK-8; 4, Synthetic
oil based on diesters; 5, Synthetic oil based on pentaerythritol
esters

Therefore the thin-film vaporization method for oils (GOST 8674-58)
permits us to distinguish oils clearly and to establish deviations in frac-
tional composition during their production.

Vaporizability

As we have already pointed out, oil vaporizability depends on its
fractional composition; in addition to a value for the total oil losses in an
engine, it characterizes a change in oil quality, since during oil vapor-
ization the low-boiling fractions are volatilized first. The nature of the
change in the oil composition curve for MK-8 oil during TRD operation is
shown in Figure 21, from which it is obvious that the greatest change in the
fractional composition of the oil occurs within the region of the low-voiling
fraction (the temperature is increased above the initial boiling point by
60-70°C.

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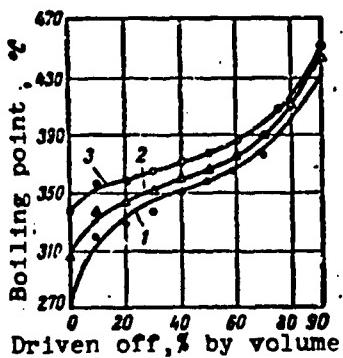
Figure 21. The fractional composition of MK-8 oil before and after TRD operation: 1, Fresh oil; 2, 3, Oil after engine operation for a period of 50 and 100 hr, respectively
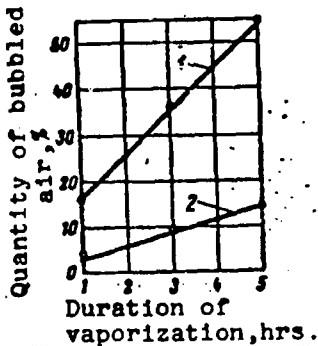
Figure 22. The influence of the quantity of bubbled air on the vaporizability of MK-8 oil at 150°C. Residual pressure in the device is 198 mm Hg. 1, 2, The quantity of air is 1.5 and 0.2 ℓ/min, respectively.

The initial boiling point of MK-8 oil is 260-270°C. In the engine the temperature does not attain this value, but nevertheless the oil vaporizes in the engine. In the process of operation air is bubbled through the oil; this air penetrates the lubricatior system of the engine and also is dispersed during operation in the gear assemblies, bearings and at the output of the oil injector jet. As a result part of the oil in an operating engine is in the form of an oil-air mixture or an oil mist. This contributes to a

significant increase in the oil vaporization surface and to the loss of the vaporized portion of the oil through the engine breathing system.

The results of laboratory tests confirm the decisive influence of the degree of air bubbling of the oil and of the temperature on oil vaporization.

It is apparent from Figure 22 that oil vaporization is directly dependent on vaporization duration and rate (quantity) of the air passed through the oil.

Notwithstanding the large quantity of air passed through the oil (1.5 ℓ/min through 100 g of oil), oil vaporization is not significant up to a temperature of 80°C (Figure 23). It has been established that at 75°C (1.2 ℓ/hr of air at a residual pressure of 198 mm Hg) oil vaporization does not occur. It becomes noticeable at 100°C, and at 150°C increases by two-three times. This explains why the viscosity of MK-8 oil during operation in the first types of domestic TRD installations remained practically unchanged. The intensive vaporization of petroleum oil begins at temperatures of approximately 120°C and above. In contemporary TRD installations the minimum oil temperature at the engine output is not less than 120-130°C, which causes its intensive vaporization.

Duration of vaporization, hrs.
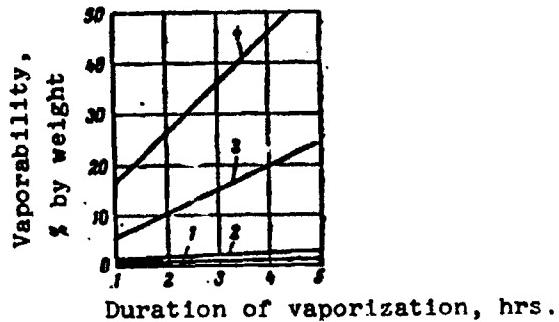
Figure 23. Temperature influence on MK-8 oil vaporization. The quantity of air is 1.5 ℓ/min, residual pressure 198 mm Hg: 1, 2, 3, 4, Vaporization at 40, 80, 120 and 145°C, respectively.

An increase in the vaporization of TRD petroleum oils with an incre se in temperature, just as for all liquids, is caused by an increase in the pressure of their saturated vapors.

It has been established that the saturated vapor pressure of American type 1010 oil increases sharply at temperatures above 80°C, and that the pressure of English oil of the DERD-2490 specification increases at temperatures above 150°C. Temperatures of this order (temperatures of intensive vaporization) for the petroleum oils indicated may also be tentatively accepted for domestic petroleum oils which have approximately the same viscosity level.

The vaporizability of TRD oils must be minimal. The total oil consumption in these engines is composed of oil losses in drop form through the breathing system and from losses as a result of vaporization itself. Therefore an increase in the viscosity of the oil in an engine or a change in the fractional composition, which is established by means of the selection and analysis of samples from an operating engine, may serve as an indirect indicator of oil vaporizability.

Operating lubricating oil consumption in a subsonic TRD on the average is 0.3-0.8 kg/hr; the authorized oil consumption according to specification is up to 1.5 kg/hr. The average hourly consumption of MK-6 oil in the engine of the TU-104 aircraft under summer conditions for 500 hr of flight operation falls within the limits 0.51-0.58 kg/hr.

In supersonic TRD installations where oil operating temperatures are higher, synthetic lubricants are employed which have lower vaporizability than petroleum oils (Table 17).

Methods of Evaluating Vaporizability

In the USSR oil vaporizability for the AGTD is determined in accordance with GOST 10306-62. The design of a device for the determination of oil vaporizability in accordance with this GOST is shown in Figure 24. Oil (100 g) is placed in the glass vaporizer, which has a device at the bottom part for air delivery and the upper part is equipped with a device for drawing off oil vapor; connections are also made here to the vacuum line and to the thermometer support. The vaporizer is placed in a thermostat. The design of the device includes a vacuum pump, a flowmeter for measurement of the quantity of air delivered, and a refrigerator for the condensation and collecting of oil vapor. The oil is vaporized in 2 hr at a specific temperature (usually at 150-175°C) by passing through it 1.5 liters of air

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in one minute with a residual pressure on the oil of 198 mm Hg, which corresponds to the pressure at an aircraft flight altitude of 10,000 m. Oil vaporizability is determined by weighing the vaporizer with the oil before and after vaporization and is expressed as a percentage.

Table 17. The Influence of Vaporization Duration on Vaporizability
and the Viscosity-Temperature Characteristics of Oils[*]
(Vaporization Method in Accordance with GOST 10306-62)

Oil	Vaporizability at 175°C		Kinematic viscosity, cs	
	Time, hr	%	At 50°C	At -40°C
MK-8			8.74	7410
	1	11.4	10.20	10400
	2	19.8	11.30	15180
	3	26.3	12.24	20430
	4	32.0	13.34	27790
	5	38.3	14.19	40380
MS-6			6.00	1440
	1	9.0	6.45	1550
	2	18.0	6.70	1670
	3	24.7	6.70	1810
	4	30.6	7.0	1940
	5	38.4	7.75	2170
M7-6			6.1	2960
	1	11.8	6.40	3770
	2	23.3	6.80	4400
	3	33.3	7.04	5300
synthetic oil based on diesters	5	5.0	3.27**	1680
			3.33**	1790
synthetic oil based on pentaerythritol esters	5	6.0	3.60**	3280
			3.73**	3630

It has been established that the use of a vacuum in the device is not required, since the basic influence on the vaporizability of oil is furnished by the quantity of air bubbled through it.

This method permits establishing the dependence of oil vaporizability on temperature, vaporization duration and other factors (see Table 17). In a two-hour evaluation of low-viscosity TRD petroleum oils by this method, the vaporizability was 18-23%, and for domestic synthetic oils, 2-3%. During

Table 18. TRD Oil Vaporizability Determined in Compliance with GOST 5737-53

Oil	Vaporizability %, at temperature °C	
	150	175
MK-8	28.4	43.0
MS-6	24.7	59.5
synthetic oil based on diesters.......	0	1.8
synthetic oils based on pentaerythritol diesters	?.4	7.3

Table 19. The Vaporizability of TRD Petroleum Oils Determined on the PZZ* Device

Oil	Vaporizability %	Kinematic viscosity at 50°C	
		Before vaporization	After vaporization
MK-8	22	8.5	13.0
MK-6			
specimen 1..........	24	6.1	9.2
specimen 2.........	18	6.1	6.3
MS-6	14	6.2	6.7
Transformer oil from Tuymazy crude	18	8.6	10.4

TRD lubricating oil vaporizability is determined in the USA by the ASTM D 972-56 method. A metal tank having a tube on the lower part for the introduction of air is placed in an oil bath. A round, closed bulb containing the oil tested is placed in the tank. The bulb is equipped with annular side openings for the delivery of air over the surface of the oil and

vaporization for 5 hr, the vaporizability of synthetic oils proved on the average to be 6-8 times lower than for petroleum oils.

Air

To vacuum pump
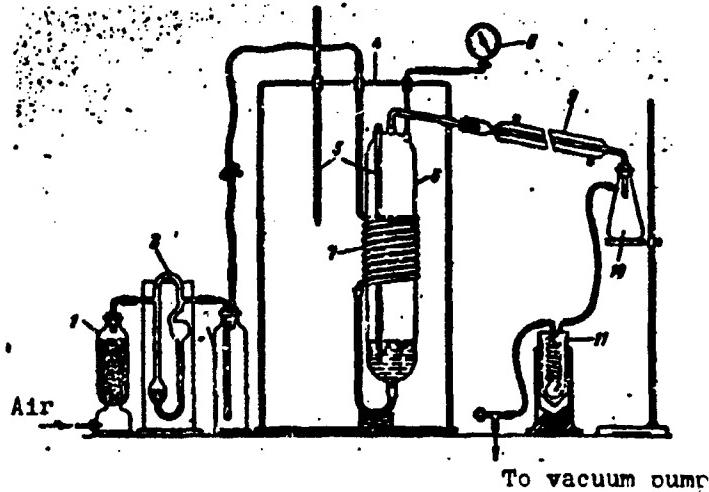
Figure 24. The diagram of a device for the determination of oil vaporizability: 1, Flask with absorbent; 2, Flowmeter; 3, Buffer flask; 4, Thermostat; 5, Thermometers; 6, Vaporizer; 7, Coil heater; 8, Pressure-vacuum gauge; 9, Refrigerator; 10, Condensate receiver; 11, Receiver-trap

The shortcomings of the vaporization method in accordance with GOST 10306-62 include the unwieldiness of the device, the necessity to conduct operations in a hot thermostat, and also the significant time expenditures required; each determination, considering preparatory work, consumes 3-4 hr.

A more promising vaporization method was suggested by K. K. Papok and B. S. Zuseva (GOST 5737-53). The total duration of the vaporizability determination by this method is 30 min. A minimum quantity of oil is required for the determination -- 0.2 g. The results of vaporizability evaluations for petroleum and synthetic oils obtained by this method are shown in Table 18.

TRD oil vaporizability is also determined on a PZZ[1] device (Table 19) from the difference in the weight of the oil before and after tests. (The PZZ device is described in detail in Chapter Six).

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[1]See p. 66

the cover is equipped with a vertical pipe for the exit of air and oil vapors from the device.

The warmed air which passes to the lower part of the air tank is directed through the annular openings in the cell, passes over the surface of the oil from all sides and after having absorbed oil vapor, passes out of the device. The test conditions are: vaporization duration 22 hr ± 5 min; oil weight 10 g; air quantity 2 ℓ/hr. The employment of this vaporization method is stipulated by the basic specifications for jet oils [51, 52]. Usually TRD oils vaporize in 6.5 hr at 204.4°C.

Footnotes

1. To p.63. The expansion of this abbreviation is unknown -- Tr.

CHAPTER FIVE

VISCOSITY AND LOW-TEMPERATURE PROPERTIES OF OILS

The Significance of Viscosity and Low-Temperature Properties

The viscosity and low-temperature properties of oils for TRD use determine the possibility of starting the engines and the pumping quality of the oil to engine friction points at low temperatures. Not only the viscosity of the oil employed, but also the smoothness of the curve of its change with an increase in temperature are of particular significance.

At the initiation of TRD development abroad, petroleum oils of high viscosity were used for 'eл. ubrication. In some of the first German TRD models oil was used with a visco·ity at 50°C of 35 cs, and in others, oil having a viscosity of 20-25 cs was ·aployed (the YuMO engine). Subsequently, however, the use of viscous oils in TRD applications was rejected. They provided for reliable engine lubrication, but at negative temperatures had very high viscosity which impeded their flow in the engine oil system. Thus at -20°C the delivery of oil with an initial velocity at 50°C of the order of 30 cs to friction points stopped completely.

The pumping quality of oils in a TRD is characterized by critical temperatures of disruption and cessation of the oil supply to rubbing parts. According to practical data these temperatures for petroleum oils which have an initial viscosity at 50°C of approximately 7 cs are approximately -43 and -51°C, respectively.

Comparative bench tests made in the USA [53] for petroleum oils with a viscosity at 50°C of 10 and 5 cs revealed that at -54°C the pressure in the oil system in the case of oil with a viscosity of 10 cs decreased rapidly, and after 10 min of engine operation had already approached zero at the output of the oil filter. In the case of oil with a viscosity of 5 cs the pressure was reduced only at the input to the oil pump, and the pressure value remained 1.5 times greater than when the first oil was used.

At the present time synthetic and petroleum oils with viscosities at 50°C from 4.5 to 11 cs are employed for domestic and foreign TRD applications. Domestic petroleum oils of the MK-8 type have viscosities at -40°C of 7,000-8,000 cs; they provide for starting of the majority of TRD installations without prewarming only to ambient temperatures of -27, -28°C. In order to start a TRD at lower temperatures, hot oil is poured into the engine engine, the oil is diluted 10-15% with jet fuel, the engine is maintained in a warm condition by periodic prewarming at low rpm, and the engine is prewarmed by hot air from airdrome starting assemblies of the APA-2M type.

The starting temperatures indicated are inadequate for ordinary TRD operating conditions. Under arctic conditions or in regions of severe low temperatures, such engine starting temperatures are even more unacceptable. This makes it necessary to employ lubricants with improved low-temperature characteristics. Such oils include the MK-6 and MS-6 domestic petroleum oils and also synthetic oils based on diesters. The American type 1005 arctic oil with a viscosity at 50°C of 3-4 cs has improved starting properties.

The low-temperature properties of domestic TRD petroleum oils to a certain extent are characterized by a pour point and a ratio of the values of kinematic viscosity at -20 and 50°C, which is expressed by a flat oil viscosity-temperature curve. These oil indicators are introduced into the standards and specifications for TRD petroleum oils. Among oils of narrow fractional composition, MK-6 and MS-6 have better viscosity ratios than MK-8, and the ratio for MK-8 is better than for transformer oil; therefore, at reduced temperatures it is more advantageous to employ MK-6 and MS-6 oils for TRD operation, and when they are not available, to employ MK-8 oil.

However, the viscosity ratio, just as the pour point, does not fully reflect oil efficiency in the engine at low temperatures. A more correct evaluation of the low-temperature oil properties for the TRD is based on the viscosity level at the minimum temperature of the employment, since it is oil viscosity itself that determines its mobility and capability of flowing to engine rubbing parts.

At a temperature of -40°C MK-8 oil viscosity has a value of 7,000 cs (Figure 25); therefore, TRD starting with this oil at this temperature is not possible.
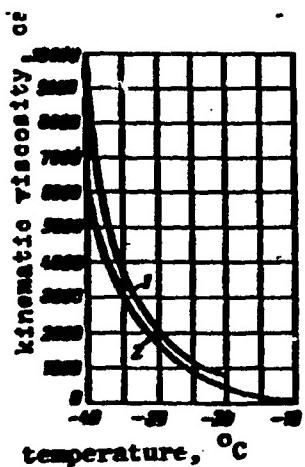
Figure 25. THD petroleum oil viscosity as a function of temperature: 1, Transformer oil; 2, MK-8

Transformer oil viscosity at -40°C is higher than for MK-8 oil (the difference is approximately 2500 cs), and its viscosity-temperature curve is placed above the MK-8 oil curve.

MK-6 and MS-6 oils (Tables 20 and 21) have improved low-temperature characteristics, and therefore the THD starting temperature without preheating may be lower with the use of these oils than with the use of MK-8 oil. Thus, in regions of severe low temperatures, THD starting without preheating of MS-6 oil is possible with temperatures from -36 to -39°C. The viscosity characteristics of MK-6, MS-6 and MK-8 oils are shown in Figure 26.

Table 20. Low-Temperature and Starting Properties
for THD Oils

Oil	Pour point °C	Kinematic viscosity at -40°C	Kinematic viscosity ratio at 50°C	Tentative minimum engine starting temperature without preheating at °C
MK-8	-55	6500-9500	54	-25
Transformer oil	-45	8600-10000	64	-21
MK-6	-60	2500-3300	43	-37
MS-6	-55	1400-1500	30	-39

Table 21. TRD Oil Viscosity at Various Temperatures

	Kinematic viscosity, cs at temperature °C							
	0	-5	-10	-20	-25	-30	-35	-40
MK-8								
specimen 1............	-	-	210	586	-	1760	-	6300
specimen 2............	-	-	211	666	-	2040	-	9464
specimen 3............	94.2	138	309	528	934	1680	3007	6913
Transformer								
specimen 1............	-	-	208	561	-	2056	-	9564
specimen 2............	96.6	148	191	592	1074	1950	3236	8560
specimen 3............	-	127	-	-	850	1500	-	8700
MK-6								
specimen 1..........	59.0	-	133	315	567	1060	2098	3300
specimen 2..........	-	-	99	210	-	600	-	3096
MS-6..................	-	-	86	187	-	490	-	1360
synthetic diester oil ...	87	-	165	341	517	845	1425	2598

Aside from an optimum viscosity level and a flat viscosity-temperature curve, TRD oils must be characterized by viscosity stability during extended engine operation. This indicator depends on oil vaporizability, which in turn is determined by its fractional composition. As we have already pointed out, MK-8 petroleum oils have a broad fractional composition and contain fractions which are easily vaporized during engine operation. Therefore at increased temperatures the viscosity of MK-8 oils increases and its poor starting characteristics show even greater deterioration (Table 22).

Narrowing of the fractional composition of petroleum oils reduces the vaporizability somewhat, but the main point is the viscosity is stabilized in the process of vaporization (Table 23).

It has been established that the higher the temperature of the oil in an engine and the longer it operates, the more intensive the increase in viscosity (Table 24).

Table 22. A Change in the Viscosity-Temperature Properties
of TRJ) Petroleum Oils During Vaporization
Under Laboratory Conditions*

| Oil | Kinematic viscosity at -40°C cs | |
	Before vapor-ization	After vaporization
MK-8	6000	22 000
MK-6	2600	4 600
MS-6	1500	1 700

* 100 g of oil was vaporized in accordance with Gost 10306-62 in a glass test tube for 2 hr at 175°C with an air supply of 1.5 ℓ/min.

Table 23. A Change in the Viscosity of MK-8 Oil and
in Blends of Narrow Fractional Composition As a Function
of Vaporizability*

| Oil | vapori-zation % | kinematic viscosity, cs | | | |
| | | At 50°C | | At -40°C | |
		Before vapor-ization	After vapor-ization	Before vapor-ization	After vapor-ization
Specimen 1	24.6	8.61	12.0	5210	14950
obtained from specimen 1 blend 329-395°C	18.2	8.39	9.61	3270	5380
specimen 2	26.3	8.61	11.0	5320	15710
obtained from specimen 2 blend 337-410°C	21.0	7.72	7.76	3200	4720
obtained from specimen 3 blend 334-385°C	25.1	6.50	7.20	2650	3280

* 100 g of oil was vaporized in accordance with GOST 10306-62 for 2 hr at 175°C with an air supply of 1.5 ℓ/min.
** In vaporizability and viscosity-temperature properties, specimen 3 is similar to specimen 2.
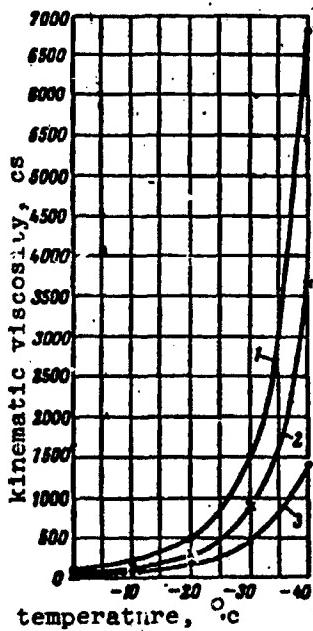
Figure 26. TRD petroleum oil viscosity as a function of temper-
ature: 1, MK-8; 2, MK-6; 3, MS-6

Table 24. An Increase in the Viscosity of Type MK-8 Oil
During TRD Operation

Oil temperature at engine output, $^{\circ}$C	Duration of oil operation without change, hr	Kinematic viscosity, cs			
		At 50°C		At −40°C	
		Fresh oil	Depleted oil	Fresh oil	Depleted oil
40 − 80	56	8.7	8.9	6700	6900
80 − 120*	25	−	−	9370	28200
85 − 115	20	8.6	10.3	6700	20200
80 − 120	51	8.2	10.3	6300	24000
* transformer oil					

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Simultaneously the pour point also changes -- it increases by 8-10°C.

The viscosity of MK-6 and MS-6 oils at 50°C is lower than for MK-8 oil and for transformer oil by approximately 2-3 cs, which also results in an improvement and in the stability of their low-temperature properties.

Therefore narrowing of the fractional composition facilitates the stabilization of the viscosity-temperature properties of oils. The viscosity of MK-6 and MS-6 oils remains sufficiently stable after 100 and even after 300 hr of TRD operation, and therefore within these time limits replacement of the oil by fresh oil is not required (Table 25).

Table 25. A Change in the Viscosity of Oils During Extended
TRD Operation Under Bench Conditions (300 hr)*

Oil	Viscosity, cs, during engine operation				
	Fresh	50 hr	100 hr	200 hr	300 hr
MK-8					
specimen 1					
viscosity at 50°C	8.9	11.6	13.5	-	-
viscosity at -40°C	8600	30000	39000	-	-
specimen 2					
viscosity at 50°C	9.1	13.0	14.7	-	-
viscosity at -40°C	8700	35000	44000	-	-
MK-6					
viscosity at 50°C	6.0	7.0	7.2	7.0	7.0
viscosity at -40°C	3096	3793	3850	3853	3589
MS-6					
viscosity at 50°C	6.0	6.7	7.0	7.0	7.0
viscosity at -40°C	1360	2024	2248	2214	2441

* MK-8 oil was replaced after every 100 hr of engine operation, and MK-6
MS-6 oils operated with no change

During 100 hr of operation in a subsonic TRD with an increased temperature condition, the viscosity of MK-8 oil at -40°C rose from 7000-7700 to 34,000-36,000 cs, and MS-6 and MK-6 oils rose from 1400 and 3000, respectively, to 2000 and 5500 cs.

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The viscosity rise and the increased pour point during TRD operation was caused not only by vaporization of the lighter part of the oil, but by oxidation processes occurring in the oil, since such oxidation products as resins remain in the oil in a dissolved state. Therefore the increase in viscosity may serve as a criterion of the intensity of oxidation of TRD petroleum oils.

The viscosity-temperature characteristics of several domestic and foreign oils are shown in Table 26.

Table 26. The Viscosity-Temperature Properties of
Several Domestic and Foreign TRD Oils

Oil	Kinematic viscosity, cs, at temperature			
	-10°C	-20°C	-30°C	-40°C
MK-8	210	585	2278	8511
transformer oil	208	561	2056	0464
type 2490 (England)	216	544	1530	5734
type 1010 (USA)	131	314	80.	2001
domestic oil on a diester base	165	341	845	2603

Viscosity stability during extended storage or maintenance under low-temperature conditions is an important TRD oil quality indicator (this pertains particularly to synthetic oils). This indicator is provided for in specifications for domestic TRD synthetic oils. This control is required because the viscosity of many chemical products employed as a base for synthetic oils changes intensively. Such a difference in oil viscosity may cause starting characteristics to deteriorate at low temperatures.

Viscosity stability at low temperatures means the capability of the oil to maintain its value at -54°C (sometimes at -40°C) after conditioning for a specified period of time at these temperatures.

A number of specifications in the USA includes the oil viscosity stability requirement. Thus, according to the requirements of MIL-L-7808D specification, oil viscosity after its conditioning for 3 hr and 30 min at -54°C must not change by more than 6% of the initial value. In addition, oil viscosity must not exceed 17,000 cs at -54°C after conditioning it at this

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temperature for 72 hr. A viscosity stability determination is included in
the specifications for domestic TRD diester oils. A change in viscosity at
-54°C after oil conditioning at this temperature for 3 hr must not exceed 6%,
and the viscosity value must not be higher than 11,700 cs.

Methods of Determining Viscosity

The viscosity of petroleum and synthetic TRD oils is determined in
capillary viscosimeters in accordance with GOST 33-66. The viscosity at
-40°C is determined in a viscosimeter with a capillary diameter of not less
than 4-4.5 mm. For research purposes the determination of oil viscosities at
negative temperatures in rotary viscosimeters such as the Pavlov viscosimeter
is authorized.

In the development and employment of AGTD oils, thickening additives or
thickening compounds such as polyisobutylene, polymethylmethacrylate,
etc. may be introduced into the oil. In these cases it is necessary to
consider the possibility of the mechanical destruction of high-viscosity
components in engine gear assemblies, which leads to a viscosity reduction
below authorized limits. The degree of mechanical destruction of the oil is
determined on the MD-1 device [54], where the oil is subjected to scuffing
in a gear pump. The operating principle of the device is quite simple and
consists of the following. Into a small oil tank of the device is placed
750 ml of the oil being tested; the oil is drawn from there by a gear pump,
heated in a coil (in order to maintain the specified oil temperature) and is
returned to the tank through a reduction valve. The pressure in the system
which is regulated by the reduction valve is 50 kg/cm^2. The oil temperature
in the tank is maintained at the specified level (60 ± 3°C) as a result of
water in the pump bath and in the coil bath. The test is conducted for
100 hr; control samples of the oil are selected every 5 sec, and then every
24, 50, 75 and 100 hr of tests.

The decrease in viscosity after 100 hr of tests in relation to oil
viscosity after 5 sec of operation in the device is taken as an indicator of
oil viscosity stability under mechanical scuffing conditions.

CHAPTER SIX

THE THERMAL OXIDATION STABILITY OF PETROLEUM OILS FOR TURBOJET ENGINES

The Characteristics of Thermal Oxidation Stability

Experience in the use of MK-8 oil in a number of TRD series reveals that insofar as thermal oxidation stability is concerned it is quite efficient with an engine output temperature of 80-100°C. For example, the average oil temperature in the VK-1 engine in practice does not exceed 80°C and the oil properties do not change during operation for 200 hr and more.

The stability of the oil is reduced (but still remains satisfactory) with increased oil temperatures at the engine output up to 120°C. Oxidation of the oil becomes noticeable if it is subjected to the action of these temperatures for an extended period of time. Table 27 shows data concerning stability deterioration of MK-8, MK-6 and MS-6 petroleum oils during extended operation in engines under bench-test conditions. During 300 hr of operation in a TRD subjected to less thermal stress, the quantity of deposits after oxidation in MK-6 and MS-6 oils attained values of 0.15 and 0.21%, respectively, and the acid number was 0.30 and 0.73 mg KOH/g.

With an increase in oil temperature at the engine output to 130-135°C, the thermal oxidation stability of the oil may deteriorate sharply; in this connection a partial oil change and a cleaning of the oil system filters with gasoline or jet fuel are required. Higher temperatures in fact have an effect on the oil in this case, since in individual friction points the oil is heated to 150-175°C.

The efficiency of MK-8 oil at high temperatures may be evaluated according to the results of laboratory investigations, which are shown in Table 28. It follows from the data in Table 28 that MK-3 oil shows insignificant oxidation up to 100°C; it maintains sufficient stability after oxidation at 120°C even for 100 hr, during which time deposits in the oil after oxidation do not exceed 0.1% and the acid number is 0.18 mg KOH/g. At an increased temperature of up to 150°C, the number of deposits after 10 hr of

oxidation increases by three times, and at 175°C after 2.5 hr of oxidation the deposits increase almost eight times in comparison with the quantity of deposits after oxidation at 120°C after 40 hr.

Table 27. The Thermal Oxidation Stability in Accordance with
GOST 981-56 of TRD Petroleum Oils As a Function of
Duration of Engine Operation

Indicator	Duration of operation of oil in engine, hr				
	0	25	50	75	100
MK-6 Oil					
acid number, mg KOH/g	0.02	0.08	0.12	0.11	0.13
stability after oxidation					
quantity of deposits, %	0.1	–	0.27	–	0.27
acid number, mg KOH/g	0.35	–	0.43	..	0.32
MS-6 Oil					
acid number, mg KOH/g	0.01	0.02	0.04	0.04	0.04
stability after oxidation					
quantity of deposits, %	none	–	0.11	–	0.12
acid number mg KOH/g	0.06	–	0.33	–	0.42
MK-8 Oil					
acid number, mg KOH/g	0.01	0.12	0.15	0.18	0.23
stability after oxidation					
quantity of deposits, %	0.07	–	0.13	–	0.20
acid number, mg KOH/g	0.28	–	0.90	–	1.28

In practice it is considered that if the quantity of deposits in the oil after oxidation comprise more than 0.40-0.60% and the acid number of the oil is more than 1 mg KOH/g, then this causes contamination of the filtering surface of the oil filters and may lead to contamination of the engine by deposits of products of oil oxidation.

Therefore, the temperature limit of the operating capability of the MK-8 oil and other oils of this type, from the point of view of thermal oxidation stability, may be considered to be 120°C during extended operation with no change for up to 100 hr.

The standard method accepted (GOST 981-56) of evaluating thermal oxidation stability for TRD petroleum oils (oxidation in a VTI device with oxygen at 120°C for 14 hr) does not permit a complete evaluation of the high-temperature properties of the oil since the conditions of this method are not

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sufficiently strict. For this reason, for example, it is not possible to detect differences in the thermal oxidation capability of various commercial barches of MK-8 oil.

Table 28. The Influence of Temperature on the Oxidizability of MK-8 Oil in Accordance with GOST 981-56

| Oxidation temperature °C | Duration of oxidation | Analysis of oxidized oil | | Condition of device after oxidation |
		acid number mg KOH/g	quantity of deposits, %	
100	40	0.04	0.02	Clean
120	40	0.09	0.04	Clean
120	100	0.18	0.11	Clean
150	2.5	0.10	0.07	Clean
150	5	0.20	0.10	Clean
150	10	0.28	0.13	small resinous deposit
150	25	1.02	0.63	dense deposit on the filter not soluble in alcohol-benzene mixture
175	2.5	0.75	0.35	abundant deposits
175	5	0.83	0.83	abundant deposits

This method of oxidation does not reproduce realistic operating conditions for MK-8 type oils in a thermally stressed TRD; therefore, in order to obtain a more correct evaluation of thermal oxidation stability, TRD petroleum oils are oxidized in accordance with a more demanding method: at 175°C for 10 hr; in the presence of ball catalysts -- copper and iron (these catalysts were also employed during oxidation in accordance with GOST 981-56); in each test tube air is delivered at the rate of 3 ℓ/hr. This is a basic method and is employed in all cases when the evaluation of the thermal oxidation stability of petroleum oils, intended for TRD operation under increased temperature conditions, is required.

It is apparent from Table 29 that oil oxidation using this method occurs much more intensively than oxidation in accordance with GOST 981-56; this makes it possible to distinguish, insofar as oxidation stability is

concerned, different commercial batches of MK-8 oil which appear to be
identical according to the standard method of oxidation.

Frequently the following instances of contamination of thermally
stressed TRD installations by the products of intensive oil oxidation are
encountered:

the appearance of a varnish film along the operating surface of the
bearings;

the clogging of the filtering surface of oil filters by solid and
semisolid products of oil oxidation -- by blackish-brown particles
approximately 1-2 mm in size. The screen of the filtering elements
of engines during operation from 40 to 70 hr with insufficiently
stable oil are clogged with deposits over 30-60% of the surface;

the deposit of a hard, abrasive residue (from 2 to 4 mm in thickness)
on the turbine bearing shell in the form of "fringes";

the appearance of the same hard deposits in the breathing pipe and in
the pipes of the fuel-oil radiator;

the formation of deposits in the jets of the oil supply injectors,
which reduces oil delivery through the injectors and causes oil
starvation of the bearings;

coking of the channels which deliver oil to the second stage turbine
bearing;

the accumulation of soft salvelike products of oil oxidation 3-4 mm
in thickness in the oil collector bushing of the turbine second stage
bearing shaft;

deposits in the form of hard pieces (such as resins) with a mass up
to 5-10 g in the oil tanks of the engines.

Engine contamination by products of intensive oil oxidation is, as
pointed out previously, a serious danger and may be a reason for an aircraft
accident.

The composition and nature of deposits which form at various places in
the lubrication system of thermally stressed TRD installations during their
operation were studied by Yu. V. Stupishin [55]. The analysis which he
conducted of deposits in accordance with GOST 2862-47 and the determination
of the content in these deposits of microelements (by means of spectrographic
analysis on the ISP-28 spectrograph) revealed that the deposits which form

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have a different nature and composition, depending on the operating conditions of the oil in the lubrication system of the engine (Table 30) [55].

Table 29. The Thermal Oxidation Stability of Petroleum Oils Determined by Different Methods

Oil	Acid number mg KOH/g	Quantity of deposit, %
Oxidation in accordance with GOST 981-56 (120°C, 14 hr. oxygen delivery 12 l/hr)		
MK-8		
specimen 1	0.18	0.08
specimen 2	0.15	0.05
specimen 3	0.20	0.04
MK-6	0.21	0.07
MS-6 (without Ionol)...............	0.34	0.14
Oxidation in accordance with more stringent method (175°C, 10 hr, air delivery 3 l/hr)		
MK-8		
specimen 1	1.58	1.34
specimen 2	1.75	1.66
specimen 3	3.04	1.55
specimen 4	1.67	1.53
specimen 5	2.00	0.96
MK-6..............................	2.30	1.48
MS-6..............................	1.26	1.49
synthetic oil based on diesters...	0.90	0.34

Thus the resin which forms in the oil tank under moderate temperature conditions consists mainly of neutral resins and asphaltenes (in various proportions), which contain a significant quantity of oxygen (11.4-20.4%). The melting point of resin is 70-90°C. The products of intensive oil oxidation such as carbenes and carboids were not detected in the resin.

Deposits on the oil filter screen and in the oil collector bushings already contain inorganic substances as a result of engine wear or the result of dust particles with air striking these surfaces. Inorganic substances are greater in deposits taken from oil collector bushings since a process of

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centrifugal separation occurs here which is accompanied by the release from the oil of the heavier products of engine part wear.

Table 30. Composition of Deposits (in %) in TRD Lubrication
Assembly Systems During Operation with MK-8 Oil

Deposits	Oil tank	Oil filter	Oil collector bushings	
			oil with no additive	oil with additive
Nature				
organic substances.......	100.0	81.4-85.6	64.9-68.4	10.2-19.6
nonorganic substances...	none	14.4-18.6	31.6-35.1	80.4-89.8
oil and neutral resins	43.5-53.6	55.?-59.2	18.5-25.3	21.4-22.5
asphaltenes...	46.4-56.2	2.6-7.7	2.12-2.15	0.65-0.83
carbenes and carboids......	none	19.5-30.6	13.15-14.06	2.24-4.80
ash...........	0-0.3	6.5-18.7	59.43-65.29	72.97-74.21
Elementary composition				
carbon	72-80	72.2-74.2	30.0-33.5	18.0-24.6
hydrogen.....	6-8	8.2-9.1	2.5-3.5	3.7-4.7
oxygen	11.4-20.4	6.4-9.2	8-9.0	8.6-10.5
sulfur	0.5-0.6	-	-	0.2-0.5
ash...........	0-2.1	9.5-11.2	55.5-57.7	62.9-66.3

With the introduction into MK-8 oil of 0.6% Ionol (MK-8p oil) the content of asphaltenes in the deposit decreases from 2 to 0.8%, of carbenes and carboids from 13-14 to 2.2-4.8%, and of organic compounds by 3-6 times.

Table 31 shows data concerning the quantity of deposits in labyrinth seals and on engine bearings as well as the influence of Ionol on deposit composition. It is apparent from these data that when an antioxidation additive is present, fractions of the deposits formed by organic compounds, as well as carbenes, carboids and asphaltenes are reduced.

The most effective influence of Ionol is on the composition of deposits formed on the rear labyrinth and on the roller bearing, which are thermally stressed to a greater degree than the front labyrinth and the engine ball bearing. It is characteristic that deposits on parts operating at higher temperatures contain a greater quantity of carbenes, attaining a value of 63.6% by weight (see Table 31), than deposits on parts with a lower operating temperature (30.6%, see Table 30).

Table 31. The Composition of Deposits (in %) on TRD Parts
During Operation with MK-8 Oil

Nature of deposit	With no additive						With Ionol additive	
	Front laby rinth	Ball bear ing	Rear laby rinth	Roller wear ing	Front laby- rinth	Ball bear ing	Rear labyrinth	roller bearing
organic substances	93.1	91.1	94.0	92.0	87.7	85.9	84.1	82.9
Inorganic substance	6.9	8.9	6.0	7.4	12.3	14.1	15.9	17.1
Oils and neutral resins	24.3	20.8	28.5	19.9	22.9	19.2	25.3	17.6
Asphaltenes	1.4	1.6	1.8	2.0	1.2	1.4	1.6	1.9
carbenes and carboids...........	56.9	54.6	60.8	63.6	50.8	49.7	51.5	53.4
ash	17.4	23.0	8.9	14.5	25.1	29.7	21.6	17.1

It is obviously possible to form an indirect judgment concerning the
temperature conditions of an engine, with respect to the intensity of oil
oxidation and changes in its hydrocarbon content from the condition of oil
deposits formed within the engine.

Oil oxidation in an engine at high temperatures is accelerated as a
result of the presence in the engines of various metals which act as oxida-
tion catalysts. The author's investigations have resulted in an .nalysis of
the catalyzing capability of various metals[1] (Table 32).

Copper and to a lesser extent steel are the most effective catalysts
in the oxidation of petroleum oils under the conditions previously indicated.
The remaining metals are relatively passive and are approximately equal-
valued. In order to evaluate the influence of the area of the metal on
oxidation, low-viscosity petroleum oil was oxidized at 140°C, with an air
delivery of 3 ℓ/hr to each test tube with copper plates of differing areas.
The most intensive oxidation was observed in tubes with plates having an area
of 7 cm^2 after 7 hr. The oxidation equaled 0.06%, and the acid number was
0.5 mg KOH/g. In tubes with plates having an area of 1.7 cm^2 after 10 hr of
oxidation there were no deposits in the oil, and the acid number was
0.38 mg KOH/g.

Table 32. The Catalytic Influence of Metals
on Oil Oxidation at 150°C*

| Catalyst | Oil viscosity | | Stability after oxidation | | Number of oxidation tests |
	At 50°C	At -40°C	Quantity of deposits,%	Acid no mg KOH/g	
MK-8 Oil (100 g oil, 10 hr, air delivery 10 ℓ/hr)					
with no catalyst	9.14	6960	0.006	0.06	4
copper.................	9.47	7970	0.348	0.62	8
steel..................	9.39	7189	0.056	0.10	4
aluminum...............	9.29	6861	0.017	0.08	6
magnesium	9.23	7595	0.013	0.09	2
silver	9.23	7640	0.021	0.09	2
tin	9.15	7610	0.034	0.07	2
zinc	9.20	7454	0.035	0.09	2
chrome	9.80	7307	0.024	0.09	2
nickel	9.17	7452	0.015	0.09	2
titanium	9.13	7400	none	0.11	2
Oil based on diesters (30 g oil, 50 hr, air delivery 3 ℓ/hr)					
aluminum	-	-	0.028	0.32	2
copper	-	-	0.134	1.57	2
lead	-	-	0.032	0.56	2

* The area of the metal plates was 10 cm^2;during the oxidation of synthetic diester oil, three plates of the metal specified were placed in each test tube.

During TRD operation oil basically oxidizes in a thin film (and not in volume), since it is sprayed on the metallic surfaces of parts in the form of a mist or as a fine oil spray. Oil is also sprayed into the drive housings of toothed gears rotating at high speeds. The oil spray which forms oxidizes while in contact with air in the hot engine parts, i.e. in these cases oxidation of oil occurs in a liquid drop state. Striking the hot engine parts, the oil oxidizes while in a thin film state. In flowing from the engine parts and from the oil sumps, the oil enters the evacuation oil pump and is again directed toward the lubrication of hot friction points and engine parts. During this process its partial vaporization occurs.

A film of oxidized oil (varnish) is usually observed along the operating surfaces of roller bearings; these are denser, more abrasive products of intensive oil oxidation and accumulate in the jets of the injectors, on the transmission housing, they are concentrated on the screening elements of fine-cleaning filters and in a number of other places. The products of intensive lubricating oil oxidation often are deposited on shaft spline couplings, and also on the turbostarter friction disks, and in places where the centrifugal separation of oil occurs, for example in the area of a secondary shaft bearing.

One of the basic requirements in the selection of a lubricant for an engine is compliance of the thermal oxidation stability of the oil with engine operating conditions. From this point of view the method of evaluating the thermal oxidation stability of TRD oils has a great deal of significance.

Laboratory Evaluation Methods for Thermal Oxidation Stability

There are a number of laboratory methods for making a preliminary evaluation of the thermal oxidation stability of lubricants. The main ones will be examined below.

Notwithstanding the fact that oil oxidation in a TRD occurs basically in a thin film or in a sprayed condition, both in the USSR and abroad up until the present time methods of evaluating oil oxidation in volume have been employed. Among these is the method of evaluation of thermal oxidation stability widely employed in the Soviet Union developed for transformer oil in the All-Union Heat Engineering Institute more than 25 years ago. Recently the stability of TRD oils has been evaluated by this method. This method is based on the oxidation of a specific volume of oil by bubbled oxygen in the presence of the oxidation of catalyzing metals, ordinarily copper and iron balls (GOST 981-56).

After a number of changes this method was placed into practice to investigate TRD oils.

However, due to the different operating conditions of TRD lubricants of various modifications and non-identical stability of the oils themselves during the employment of this method, different temperatures, air quantities, etc have been employed.

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Available generalized experience in the employment of various modifications of this method in the USSR indicates that currently an evaluation of the thermal oxidation stability of TRD oils for research purposes is accomplished under the following conditions: the temperature is 140-220°C; the quantity of air for oxidation is 50 to 250 ml/min; oxidation duration is 5 to 72 hr; and the catalysts are plates of 2 to 7 metals.

As we have already pointed out, the volume method of oil oxidation unsatisfactorily reflects the oxidation process in an engine. In order to judge correctly the tendency of an oil toward deposit and coke formation during TRD operation, it is necessary to determine its thermal oxidation stability not only in volume, but also in a thin film.

Methods previously developed in the USSR for the investigation of the oxidizability of oils in a thin film [56] were intended for the evaluation of the stability of oils employed in piston engines, although some of these, in principle, may be successfully employed in the area of low-viscosity TRD oils. Recently a number of methods of evaluating the stability of jet oils in a thin film have been developed and applied; among these are the Shmelev method, the Papok and Zuseva method of thin-film oxidation, and others [57-60].

In accordance with Shmelev's method, a thin oil film is oxidized on a heated metal surface. Oil at a specified rate of drop formation is delivered to a metal plate, heated to an established temperature, which is located in a special chamber. The oil flows along the inclined plate, is oxidized by atmospheric oxygen in the presence of the catalytic effect of metal and forms a carbonaceous deposit on the plate. The quantity of air in the oxidation chamber is maintained at a specified level. Thin-film oil stability is judged mainly by the quantity of deposits on the plate (in mg), by the change in the physicochemical properties of the oil after oxidation and by the composition of the deposits (GOST 2862-47). Simultaneously vaporizability of the oil is evaluated from the difference between the quantity of oil subject to oxidation and the quantity remaining in the device after oxidation.

The design of the device is shown in Figure 27. The device consists of reaction chamber (8), in which metallic plate (12) is placed on the heater at a 45° angle; the temperature of the plate is kept constant during the test.

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Oil from small tank (1), which is equipped with a heater, drops to the plate through measuring valve (4) at a specific rate, flows from the plate and is collected at the bottom of the chamber. The air which enters the hermetically sealed reaction chamber is regulated by means of flowmeter (15), and the air which is evacuated from the chamber is regulated by a vacuum pump.
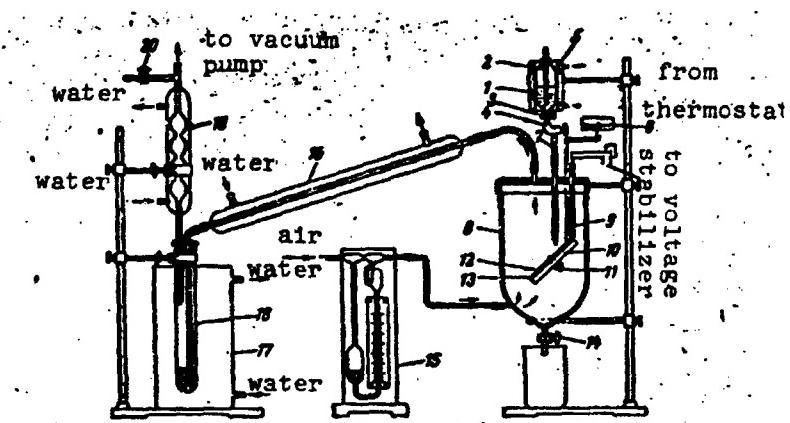
Figure 27. The design of a device for thin-film oil oxidation on a panel: 1, Small tank for oil; 2, Thermometer; 3, Valve; 4, Regulating valve; 5, Small tank heater; 6, Galvanometer; 7, Glass pipe; 8, Reaction chamber; 9, Thermocouple; 10, Heater; 11, Clamp; 12, Test plate; 13, Gasket; 14, Drain valve; 15, Flowmeter; 16, Receiver; 17-19, Refrigerators; 20, Air valve

The test conditions are as follows: the quantity of oil poured into the small tank, 50 ml; duration of pumping of air through the chamber, 3 ℓ/hr; rate of oil drop formation 0.5 ml/min; duration of experiment 100 ⁺ 3 min.

It is possible to oxidize oil on plates of various metals at different temperatures. Figure 28 shows the relationship between the quantity of the deposits and the temperature of the plate, which permits us to compare the thermal oxidation stability of different oils.

In order to evaluate a change in oil stability during multiple oxidation in a thin layer (which more closely reflects oil oxidation conditions in an engine) it is advantageous to pass the same oil through the device several

times, while comparing the thermal oxidation stability of fresh oil and oil
which has been subject to multiple oxidation (Figure 29), as well as with oil
after extended operation in a TRD.
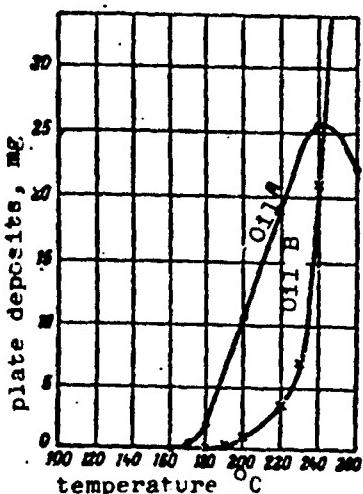
Figure 28. The thermal oxidation stability characteristic of
petroleum oils in a thin film

Table 33 shows the results of investigations of TRD petroleum oils in
accordance with the method described. MS-20 oil is characterized by a small
tendency toward the formation of a varnish film.

Table 33. Tendency of TRD Petroleum Oils Toward Formation of a Varnish Film

| Oil | Quantity of deposits on aluminum plate at temperature ^{o}C | | | | |
	180	200	220	240	260
MK-8	0.0030	0.0096	0.0201	0.0258	0.0232
MS-6	0.0012	0.0055	0.0075	0.0042	0.0038
MK-6	0.0007	0.0013	0.0025	0.0037	0.0021
MS-20	0.0103	0.0159	0.0416	0.0694	-
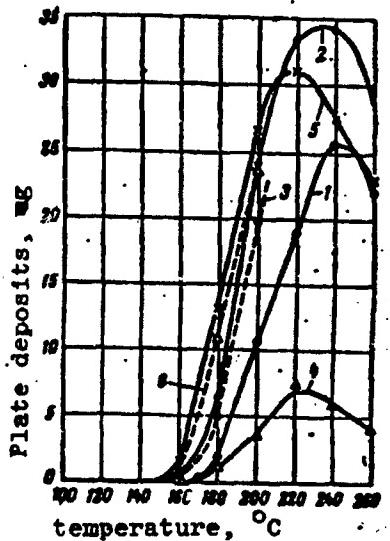
Figure 29. The convergence of the results of multiple thin-film
oxidation of oils with the results of their oxidation in a TRD:
1, Oil A, fresh; 2, Oil A, after 300 hr of engine operation;
3, Oil A after four-stage oxidation in a test device; 4, Oil C,
fresh; 5, Oil C, after 300 hr of engine operation; 6, Oil C
after four-stage oxidation in a test device

The most oxidation-resistant oils proved to be those of narrow
fractional composition.

The Pratt-Whitney method is used *- the United States, which permits
evaluating the tendency of oils toward the formation of carbon deposits on
engine parts at high temperatures. The oil is oxidized in a thin layer using
a special device. The oil in this device is located in a special inclined
tray. An electric heater with an aluminum plate is located above the tray.
Oil is sprayed on the hot aluminum plate by means of a rotating shaft with a
toothed comb-like structure, where it is oxidized. Tests are conducted for
eight hours; the thermal oxidation stability of the oil is evaluated in
accordance with the mass of the coke formed on the plate. Not more than
100 g of deposits are authorized.

The most promising of these methods for evaluating TRD oils are those in
which it is possible to determine not only the thermal oxidation stability,
but also a number of other oil characteristics associated with this

characteristic. For example, in the USA a method is employed for evaluating the petroleum oils Turboil-1 and Turboil-2 (specification MIL-O-6081B), which permits the simultaneous determination of corrosion properties and stability after oxidation for 168 hr at 121°C by means of plates of copper, steel, aluminum alloy, magnesium alloy and cadmium steel.

The corrosion activity and thermal oxidation stability of the oil is evaluated by three indicators: these include the corrosion of the metals indicated (not more than ±0.2 mg/cm^2); a change in viscosity, determined at 37.8°C (within the limits from -5 to 20%), and an increase in the acid number (not more than 0.2 mg KOH/g).

Evaluating the Thermal Oxidation Stability on Special Devices

Of the special devices employed abroad for the evaluation of thermal oxidation stability of oils, the devices of Nepir and Wright [61] deserve attention.

In Nepir's device oil is oxidized at 280°C in ball bearings, rotating at a rate of 21,000 rpm; 1.7 l/hr of oil is circulated through each bearing. The test is conducted in cycles until the appearance of significant deposits or until the bearings are damaged. The test cycle includes an increase in oil temperature for 45 min to 280°C and operation at this temperature for 6.5 hr.

In Wright's device oil is oxidized for 7 hr at a rotating bearing speed of 8300 rpm; the temperature of the external bearing yoke is 382°C. Oil flows through each bearing at a rate of 0.3 l/hr.

Most promising is the domestic PZZ device [58] which was previously employed mainly to check the quality of motor oils. With this device it is possible in a short period of time to determine fully the stability, vapor-izability and corrosion properties of TRD oils.

The PZZ device (Figure 30) is a circulation system consisting of oil tank (2) with electrical heater (3), special cassette (7) in which eight metal plates are located and oil pump (5) which is rotated by electric motor (6).

The test oil (250 ml), heated to the required temperature (usually 150°C), is delivered by the oil pump at the rate of 125 l/hr from the feed tank to the cassette with plates; the oil washes the plates, then flows

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through the pipe to the upper part of the tank and is sprayed on the heated
sides of the tank; after this the oil flows downward and again circulates
through the device. The pressure pump of the device delivers air (50 ℓ/hr)
for two hours.
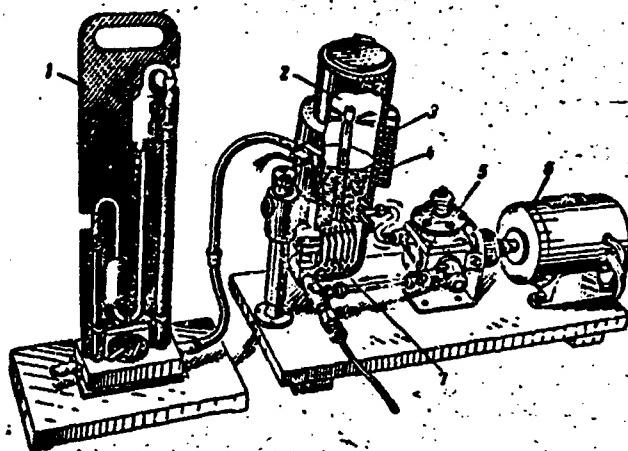
Figure 30. A PZZ device for the evaluation of the operating
properties of jet oils: 1, Flowmeter; 2, Small tank; 3, Electric
heater; 4, Oil; 5, Pump; 6, Electric motor; 7, Cassette with
plates

Thermal oxidation stability of the oil is judged by the acidity,
viscosity and quantity of deposits in that part of the oil remaining after
oxidation. Oil vaporizability is determined by the quantity difference
before and after testing.

The PZZ device permits determining in two hours the thermal oxidation
stability of TRD oils (Table 34) and the effectiveness of the introduction
into these oils of antioxidation additives.

Methods of Improving the Thermal Oxidation Stability

Domestic TRD petroleum oils which contain no antioxidation additives
resemble each other in thermal oxidation stability but MS-6 oil is somewhat
inferior in this respect to MK-6 oils (Table 35) and MK-8 oils (see
Table 29).

Table 34. The Stability of TRD Petroleum Oils,
Determined on the PZZ* Device

Oil	Acid no. mg KOH/g		Quantity of deposits after test,%	Viscosity at 50°C, cs	
	Before testing	After testing		Before testing	After testing
			At 150°C		
MK-6	0.03	6.49	3.6	6.1	9.2
MK-6 +1.7 % Ionol	0.03	0.03	0.4	6.1	6.3
			At 175°C		
MK-8	0.04	2.50	0.35	-	-
MK-8 +1% Ionol	0.04	0.18	0.20	-	-
			At 200°C		
MK-8	0.04	2.89	1.1	8.1	13.1
MK-8 + 1 % Ionol	0.04	1.57	0.6	8.1	10.4

* The data were obtained by A. P. Zarubin

The thermal oxidation stability of petroleum oils is a result of their different chemical group composition, i.e. the presence and peculiarities of the structural composition of their component hydrocarbons. The chemical group composition of TRD petroleum oils and its influence on the basic operating properties of oils is discussed in more detail in Chapter Eleven. Here we shall point out only that MS-6 oil from Tuymazy crude contains an insufficient number of natural antioxidants, i.e., aromatic hydrocarbons of a specific structure.

The thermal oxidation stability of MS-6 oil is increased to the level of this indicator for MK-8 oil by the introduction of the antioxidation additive Ionol (GOST 10894-64) during plant production.

It is apparent from the data in Table 35 that MS-6 oil has good Ionol susceptibility. Thus after the addition to the oil of 0.2% Ionol, deposits

after oxidation of the oil at 120°C were lacking and the acid number was only 0.15–0.17 mg KOH/g, which exceeds the requirements of GOST 6457-66. The introduction of larger quantities of Ionol gives less effect and is therefore not advantageous since the cost of the oil increases. MS-6 oil oxidation at increased temperatures by a more stringent method (see Table 35) also confirms the high Ionol susceptibility of MS-6 oil.

Table 35. The Thermal Oxidation Stability of MS-6 and MK-6 Oils

Oil	Ionol Content %	Stability after Oxidation	
		Acid No. mg KOH/g	Quantity of deposits,%
Oxidation in accordance with GOST 981-56			
MS-6			
specimen 1	-	0.46	0.12
specimen 1	0.2	0.15	none
specimen 2	-	0.32	0.09
specimen 2	0.2	0.17	none
MK-6			
specimen 1	-	0.33	0.08
specimen 2	-	0.34	0.05
specimen 3	-	0.34	0.03
Oxidation at 175°C (the stringent method)			
MS-6			
	-	1.70	1.82
	0.5	0.26	0.72
	0.75	0.13	0.42
	1.00	0.03	0.28
	1.50	0.01	0.16
MK-6			
	-	2.30	2.68
	0.5	2.27	2.61
	0.75	1.86	1.89
	1.00	1.80	1.84
	1.50	0.19	0.61

MK-6 oil satisfies the stability requirements of GOST 6457-66 without the addition of Ionol.

The thermal oxidation stability of MK-8 oil, intended for thermally stressed TRD applications, is improved somewhat by the introduction of 0.6% Ionol. The oil operates satisfactorily in thermally stressed TRD installations when it is changed and the oil filter cleaned after each 50 hr of engine operation. The quantity of deposits is less than in the case of the use of MK-8 oil without an additive.

For the overwhelming majority of commercial batches of MK-8p oil, with the correct choice of a base (Balakhany petroleum oil), the introduction into MK-8 oil of 0.6% of the additive Ionol guarantees that in compliance with GOST 6457-66 the quantity of deposits after oxidation will not be more than 0.15% and the acid number will not be more than 0.6 mg KOH/g (Table 36).

The thermal oxidation stability of MK-8 oil may be increased by adding to it other antioxidation additives, for example, paradiphenylamine oxide, the AzNII-levin additive, etc. [62].

Table 36. The Thermal Oxidation Stability of MK-8 Oil with the
Addition of Ionol*

Specimen No.	Ionol content %	Stability after oxidation	
		Acid No. mg KOH/g	Amount of deposits %
Oil Requirements which satisfy the GOST 6457-66			
Specimen 1	–	1.58	1.34
"	0.5	0.56	0.15
"	0.6	0.12	0.004
"	0.7	0.07	0.007
Specimen 2	–	1.75	1.66
"	0.6	0.60	0.14
Specimen 3	–	1.67	1.58
"	0.6	0.11	0.02
Specimen 4	–	2.00	0.96
"	0.5	0.17	None
Specimen 5	–	0.83	0.86
"	0.6	0.19	0.02
Specimen 6	–	0.75	1.00
"	0.6	0.42	0.10
Specimen 7	–	0.87	0.82
"	0.6	0.19	0.01
Specimen 8	–	1.67	1.58
"	0.6	0.30	0.05
Specimen 9	–	0.87	0.82
"	0.6	0.18	0.03
Specimen 10	–	0.93	1.08
"	0.6	0.50	0.28
Specimen 11	–	0.87	0.82
"	0.6	0.19	0.01
Oil specimens which do not satisfy the GOST 6457-66			
Specimen 1	–	0.93	1.08
"	0.6	0.64	0.28
Specimen 2	–	0.96	1.10
"	0.6	0.64	0.36
Specimen 3	–	1.67	1.66
"	0.6	0.80	0.45
Specimen 4	–	0.91	0.98
"	0.6	0.76	0.61
Specimen 5	–	0.96	1.10
"	0.6	0.64	0.36
Specimen 6	–	1.67	1.66
"	0.6	0.80	0.45

* Oxidation was accomplished at 175°C for 10 hr, and the rate of air delivery was 3 ℓ/ hr.

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Footnotes

1. To p.82. The laboratory work was conducted by G. i. Krylova and others.

CHAPTER SEVEN

THE LUBRICATING AND ANTI-WEAR PROPERTIES OF OILS FOR TURBOJET ENGINES

The Significance of Lubricating and Anti-wear Properties

Lubricants employed in a TRD must protect antifriction bearings and gear transmissions from increased wear, must prevent the jamming of rubbing parts, and must provide for reliability and longevity in engine operation during the period of service of the resource.

The nature and degree of wear of rubbing parts is determined by their design and operating conditions (loads, the rates of rotation of rubbing couples, temperature, etc.), and also by lubricant properties.

The use of antifriction bearings in the main TRD operating assemblies permits us to employ low-viscosity lubricants in these engines; the gear drive transmissions of various assemblies transmit relatively low power (200-600 hp), bear loads up to 40-50 kg per 1 rа of tooth width and therefore do not determine the choice of lubricant type and quality. However, due to small dimensions and low weight, these friction points are stressed to a degree which requires lubricants of high quality.

The lubricant supplied to the antifriction bearings reduces the friction between rolling bodies and the rings, between rolling bodies and the cages, and also between the cages and the ring flanges. In filling the gaps between bearing parts, the oil provides for greater elasticity in bearing load acceptance, removes heat from the bearing and protects it from corrosion.

It must be considered that the lubricating (anti-wear) properties of oil are determined by its load-carrying capacity (the capacity of an oil film to accept and withstand a load without being forced from the gaps between rubbing parts) and its lubricity which provides for the creation of a firm film on the surface of the rubbing pairs.

The load-carrying capacity of the oil is determined by its viscosity [63]. In agreement with the hydrodynamic theory of lubrication [64] the

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load-carrying capacity of an oil film is determined by the viscosity of the oil and by the rate of relative displacement (sliding) of the rubbing surfaces. The higher the viscosity of the oil and the sliding rate, the higher are load-carrying capacity of the oil layer.

Based on these statements, oils with high viscosity are preferred; however, as a rule, they are characterized by poor low-temperature and starting properties. In addition a reduction in the viscosity of oils employed in the TRD is permissible only to a specific limit, since low-viscosity oils cause an increase in pox-like wear (pitting), which is characteristic for toothed wheels and antifriction bearings. The most probable hypothesis for the formation of pitting states that during high temperatures and high cyclic contact loads, fatigue cracks form as a result of shaking with slippage on rubbing surfaces. Subsequently, due to the wedging effect of the oil [65], these cracks are transformed into pitted ulcers on the metal surface. Oil having low viscosity penetrates easily under pressure into the microcracks in the metal. The work of a number of researchers [66-68] has revealed that pitting is reduced with the use of high-viscosity oils.

Therefore in choosing oils with optimum lubricating characteristics their viscosity properties must be taken into consideration, as well as the design peculiarities of the mechanisms for which the oils are intended.

The viscosity of petroleum and synthetic oils employed in the TRD falls mainly within the range 5-10 cs at 50°C, although in some cases petroleum oils with a viscosity of 4-4.5 cs are employed.

Abroad it is considered that reliable lubrication of the TRD in the range of high temperatures is provided by means of a lubricating oil with a viscosity of not less than 3.0-3.5 cs at 100°C.

If the rubbing surface is not fully coated with a layer of oil, i.e., the liquid lubrication is not complete, which is characteristic for gear trains and antifriction bearings, wear and sticking of the surfaces no longer depend on oil viscosity, but on the lubricating properties or lubricity of the oil, which is determined by the capacity of the oil to form firm cross-linked layers with the correct distribution of oriented molecules on the surface of the metal.

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This high orientation capacity on the surface of the metal is possessed by surface-active substances contained in the oil. Such substances are naphthenic and carboxylic acids, resins, asphalt-resin products, sulfur compounds, etc. Here we must also consider oxygen-containing compounds which form during the oxidation of oil, and also the various additives introduced into petroleum and synthetic oils [69-70].

The lubricating properties of petroleum oils which show little difference in viscosity are quite close, which has been confirmed by investigations.

The extended operation of subsonic mass-produced TRD's with such petroleum oils as MK-8 and transformer oil reveals that these oils provide reliable lubrication of engines during the entire period of their service. In connection with the increased operating temperatures in supersonic TRD's, it is necessary to enhance the lubricating capacity of oils. Recently, therefore, a great deal of work has been accomplished in investigating and selecting anti-wear additives for petroleum and synthetic TRD oils.

The lubricating properties of TRD oils both in the Soviet Union and abroad are evaluated according to various methods with the use of diverse laboratory friction machines, including special devices and stands.

Methods of Evaluating Lubricating Properties

The Four-Ball Friction Machine

In the USSR and abroad the anti-wear properties of TRD oils are preliminarily evaluated on a four-ball friction machine.

In different design versions of the four-ball friction machine a pyramid of three fixed balls in one movable upper ball serve as the main operating friction point. By means of the four-ball friction machine, as demonstrated by V. A. Listov, the comparative characteristics of the anti-wear properties of oils may be obtained by the so-called step loading method (usually the one-minute method), by tests for film longevity at constant load and by other methods [71-72].

Usually the lubricating properties of TRD oils are investigated on the four-ball friction machine under room temperature conditions by means of th the one-minute method, employing steel balls with a diameter of 9.5 or 19 mm;

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the rate of rotation of the machine rotar is 1400 rpm. As a result the critical oil film breakdown load (P_k) and the diameter of the wear trace (in mm) at P_k are determined. Since dry friction is not permissible in a TRD and the oil must provide for the operation of rubbing parts with minimum wear without sticking, the results of investigation on the four-ball friction machine, obtained in the region of subcritical loads, are of great interest.

Table 37 shows the results of an investigation of the anti-wear properties of TRD petroleum oils on a four-ball machine at usual temperatures in accordance with the one-minute method with balls having a diameter of 9.5 mm.

Table 37. The Anti-wear Properties of TRD Petroleum Oils

Oil	Maximum load for disruption of the oil film P_k, kg	Anti-wear properties	
		Wear trace diameter at P_k, mm	Ratio of MS-20 oil P_k to P_k of remaining oils
MK-8	28	0.39	1.79
MK-6	33	0.36	1.53
MS-6	30	0.37	1.67
transformer	30	0.36	1.67
MS-20	50	0.38	1.0

A Stand with a Free Overrunning Shaft

In accomplishing investigations, the lubricating properties of oils are evaluated on a stand proposed by I. G. Shmelev. The basic operating part of the stand is a shaft, installed in ball bearings. The speed of shaft rotation is increased to a specific number of rpm, then the drive is disconnected and the shaft rotates to a complete stop. Tests are conducted with a load on the shaft and without a load. Data concerning the lubricating capabilities of oils, determined by this method, are shown in Table 38.

The greater the lubricating capacity of the test oil, the higher the number of revolutions the shaft will make before seizing, or the higher will be the ratio of the number of shaft revolutions with a load to the number of shaft revolutions with no load. It is considered that the stand with a free overrunning shaft permits determining the lubricating capacity or the lubricity of the lubricating material tested.

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Table 38. The Lubricating Capability of TRD Petroleum Oils Determined
in Accordance with the Free (Bearing) Shaft Overrun Method*

Indicators	Total number of of shaft revolutions from 3000 rpm to a stop	
	MK-6	MK-8
At 20°C		
with no load (a)	23,320	18,190
with 200-kg load on on the bearings (b)	7,118	6,445
ratio a:b	3.3	3.8
At 100°C		
with no load (a)	30,756	33,005
with bearing load of 200 kg (b)	3,324	7,995
ratio a:b	3.7	4.1

* These data were obtained by I. G. Shmelev.

The Friction Machine of Klimov and Vilenkin (KV-1) [73]

The KV-1 friction machine is employed in order to evaluate the anti-wear properties of jet oils. It is considered that according to surface friction conditions the machine approximates a number of actual mechanisms, for example, gear trains. In this machine (Figure 31) the friction pair is formed by roller (1) (which is stationary or which is rotated by an independent drive) and coil (2) of special wire, which is wound along a spiral channel of rotating disk (3). Since the coil is wound on disk (3) in a spiral, the place of contact of the coil and roller (1) during disk rotation constantly changes and each point of the combined friction surfaces comes into contact one time in one revolution of the disk.

The load at the friction point is created by hydraulic loader (6) and is controlled in accordance with manometer (8). The machine has a device (7) for rapid load application and removal. Replaceable disks (3) have diameters from 34 to 210 mm; the oil in bath (9) and the friction pair submerged in it may be heated to 200°C; disk rpm is controlled with the aid of stroboscope (4). The speed of rotation of disk (3) may be adjusted within the limits of 100-2800 rpm.

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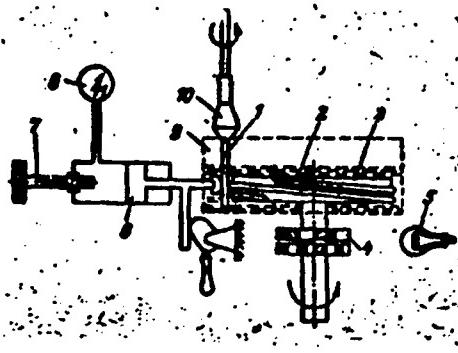
Figure 31. Diagram of the KV-1 friction machine: 1, Roller;
2, Coil; 3, Disk; 4, Stroboscope; 5, Neon lamp; 6, 7, Loaders;
8, Manometer; 9, Bath; 10, Clamping chuck

The design characteristics of the machine permit evaluating the anti-wear properties of petroleum products at friction pair sliding rates of 0.2-30 m/sec, at specific pressures up to 50,000 kg/cm^2 and at temperatures to 200°C (Table 39).

Table 39. The Anti-wear Properties of TRD Petroleum Oils Determined on the
KV-1 Machine

Oil	Critical seizing load P_k at friction pair sliding rates		
	2 m/sec	5 m/sec	10 m/sec
MK-8	17.0	5.0	3.0
MK-6	15.0	4.1	2.4
MS-6	16.7	4.7	2.5

The tests are conducted in the following manner: the temperature is established in bath (9) and the rate of rotation of disk (3) is established up to specified values and a step load is applied to the friction pair (each step is not more than 10% of the seizing load P_k); the dur--ton of the load application and intervals between loads are 10 sec. The oil is tested until galling appears on the friction surfaces.

The seizing load is determined at different disk rotation speeds and then curves are plotted showing the stalling load as a function of sliding rate or temperature.

The main shortcoming of all laboratory type friction machines consists of the fact that they do not reproduce the actual operating conditions of lubricating oils in mechanisms. Therefore, the comparative indicators of anti-wear properties of oils obtained on these machines are preliminary evaluations and do not solve the problem of the possibility of employing the oils in engines.

For a conclusive selection, the oils are tested on highly stressed special installations or in the engines themselves.

Closed Circuit Gear Devices

Domestic installations of this type (Sh-3, Sh-15, etc.) consist of a gear stand, two isolated oil systems and a control panel. The stand operates on the closed circuit system, and includes a front housing with a pair of test gears and a separate oil system, and a rear housing (closing gears) with its oil system.

The oil system of the stand includes oil pumps, coarse- and fine-cleaning filters, flowmeters, thermocouples, manometers and other equipment. The gears are manufactured in accordance with the sixth precision class-ification.

The gears are loaded by rotating the shafts with the loading coupling by means of levers and weights. The gears in which the oil is tested (11,600 rpm) have diamters of 55 and 110 mm; the peripheral velocity of the small gear with respect to the initial circumference is 33.4 m/sec. Ten liters of oil are used for the test; the pumping radius 2-2.5 ℓ/min; the oil temperature at the input of the gear assembly is $75 \pm 5°C$.

The testing begins after washing of the stand, rolling of the gears and preparatory work. The oil is tested for 50 hr with a load on the gears (torque) of 8.8 kg/m and a contact stress on the face of the gear engagement tooth of 16,700 kg/cm^2. Depending on the purpose of the test oil, its temperature and the gear load may be changed.

The test consists of five stages of 10 hr each (50 hr in all): after each stage the gear teeth are examined without disassembly of the housing.

The anti-wear properties of the oil are evaluated in accordance with the external appearance of the gears (scratches, graduation lines, galling damage, etc.), and in some installations also by means of comparing

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profilograms or involutes of the teeth before and after testing. The results
of experimental TRD oil tests are compared with the results of tests for MK-8
oil, the anti-wear properties of which are accepted as a standard.

During tests in installations of this type, the quality of oils changes
noticeably (Table 40). Therefore an analysis of the physicochemical proper-
ties of oil before and afte. ... te:t permits judging the thermal oxidation
stability, vaporizability anu the change in viscosity peroperties.

Table 40. A Change in the Quality of MK-6 Oil During the Test Process
in an Sh-3 Device

Specimen	Kinematic viscosity, cs, at		Acid No. mg KOH/g	Quant'ty of deposits insoluble in isooctane, %
	50°C	-40°C		
fresh oil	6.01	2108	0.01	-
after 10 min operation	6.15	-	0.02	-
after 10 hr operation	6.27	-	0.07	0.0079
after 20 hr operation	6.51	-	0.13	0.0086
after 30 hr operation	6.69	-	0.26	0.0225
after 40 hr operation	7.08	-	0.57	0.0693
after 50 hr operation	7.63	3583	1.10	0.3781
condensate				
from refrigerator of device	4.48	-	1.23	-
from device pipelines	4.57	-	1.77	-

The results of oil tests in gear installations of the type described
coincide satisfactorily with the results of bench tests of these oils in a
TRD. In order to obtain repeatable results during parallel oil tests in
these devices, it is necessary to employ gears for these tests which are
identical insofar as the quality of the metal is concerned, and also insofar
as gaps and tolerances are concerned. Otherwise an incorrect result may be
obtained. To a certain extent this may be considered as a shortcoming of
gear installations.

The Evaluation Abroad of Anti-wear Properties
The Rider Machine

In the USA the anti-wear properties of AGTD oils are evaluated on the
Rider machine of the Pratt and Whitney " firm [74]. The gears of a TRD
(Figure 32), which have an identical number of teeth (28 each), serve as the
operating friction point of the machine. Therefore, during operation of the

gears, engagement occurs along the surface of the same matching teeth, which may also be observed in several domestic devices of this type. The test oil is delivered at a rate of 270 ± 5 mℓ/min to the gears at the point of their disengagement. The gear rate of rotation is 10,000 ± 100 rpm, but this may be increased to 16,000 rpm; the temperature of the oil tested is 74 ± 3°C; the total quantity is 500 mℓ. The load on the gears is increased in steps after each 10 min of operation of the stand. The tests are made up of several 10-min cycles; after each cycle the number of scratches or galling marks which appear on each tooth are counted.
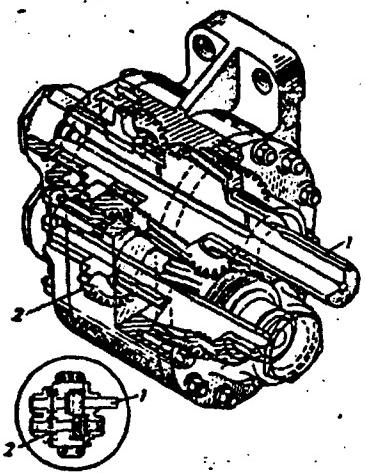
Figure 32. The Rider machine for the determination of anti-wear properties of oils: 1, Electric motor shaft; 2, Testing gears

Oil quality is evaluated by critical load (load-carrying capacity) at which scratches and galling damage appear on one-third of the surface of 66% of the teeth. The critical load is expressed in kg per 1 cm of tooth width. The Rider machine does not give reproducible results, since it is difficult to select gears of identical quality. Each oil is tested several times and then the results are compared with the test results of 1100 standard oil, type V (the critical load value is 480-570 kg/cm).

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According to the MIL-L-7808D specification, a critical load value comprising 68% of the critical load of the standard oil is authorized established according to the results of eight tests. However, it is considered that the requirements of the specification indicated are not very strict. Therefore, for example, in the MIL-L-25336 specification (1956) the oil anti-wear property requirements for TRD reducers have been raised. In agreement with the MIL-L-23699 specification, the critical oil load tested on a Rider machine at 74°C, must be 418-581 kg/cm. These same requirements for oil are imposed by the English specification DERD-2497.

It has been experimentally established that oils which withstand a load on the Rider machine of not less than 300 kg/cm may be successfully employed in a TRD. Oils are recommended for TVD use which have withstood a critical load of approximately 450 kg/cm on the Rider machine.

The IAE Test Stand

This test stand was developed in England and is intended for testing the anticorrosion properties of TVD oils. In technical and design configuration, it differs from the Rider machine only in that the driving and driven gears have a different number of teeth -- 15 and 16, respectively; therefore, the order of tooth engagement during gear operation changes.

Tests are conducted at a temperature of 110°C, and the pumping oil rate is 235 ml/min, and the rate of rotation of the driven gear is 2000 to 6000 rpm. The gears operate with an increasing load, five minutes for each step, until the onset of galling, which is established by a reduction in the speed of the gears. This installation, just as the Rider machine, does not give good reproducible results; therefore, the tests are repeated several times and the results are compared with the data from a standard oil.

A Test Stand with Truncated Friction Cones

Unsatisfactory reproducibility of the results of anti-wear properties of oils determined on gear friction machines is explained by the difference in quality of the groups of gears employed. The English firm "Bristol Siddley" employs a test stand in which the friction gears are replaced by truncated steel cones which have an average diameter of 150 mm, an inclination angle of 90° and a contact surface 18 mm in width. The friction surfaces of the cones are polished to a smoothness of $1.0-1.25 \cdot 10^{-4}$ mm and

are case hardened. The speed of rotation of the cones may be changed from 2400 to 9000 rpm, and the sliding rate may be changed from 4.1 to 18.4 m/sec. During operation the cones come into contact along the surface face so that the sliding rate along their width changes. The capacity of the oil system is 16 ℓ, the oil flow rate is 118 ℓ/hr. After each 15-min period, the load on the cones is increased until the oil film is disrupted, which is determined by a temperature increase in the contact line zone of the cones.

According to the DERD-2487 specification, the oil temperature at the input to the cones is maintained at 110°C, and according to the DERD-2497 specification, at 200°C for synthetic oils.

Reduction Test Stands

The anti-wear and anti-galling properties of AGTD oils are evaluated abroad in a number of cases in special reduction devices. Thus the "Rolls Royce" company tests oils on the Dart reducer with a power of 2400 hp for 150 hr and with a reduction gear rotation speed of 1500 rpm and an oil temperature at the input of 115°C. Similar tests are accomplished in the Tine reducer. Oil test conditions in reducer installations are more stringent than in the Rider machine and correspond to the operating conditions of oils in TRD's. In addition to load-carrying capacity, the tendency of oils toward scale and precipitation formation is also determined on these devices.

An Investigation of Lubricating Properties

Notwithstanding the significant difference in the viscosities of oils for jet engines and oils for aviation piston engines, in lubricating capability MK-8 oil is not far inferior to MS-20 oil, for which this indicator is relatively high. Thus, the ratio of critical oil film breakdown loads (P_k) (determined by the one-minute method on a four-ball friction machine with balls 19 mm in diameter) for MS-20 and MK-8 oils is 1.5 (Table 41).

The difference in critical loads is also preserved during a temperature increase from 20 to 100°C. The higher ratio of critical loads (1.8), determined on a friction machine with balls having a diameter of 9.5 mm (see Table 37), is explained by another quality of the oils selected for testing.

Table 41. The Anti-wear Properties of Oils* at Various Temperatures
Determined on a Four-Ball Friction Machine

Indicator	MK-8 oil	MS-20 oil
At 20°C		
critical oil film breakdown load P_k, kg	41 -45	62 - 68
width of wear of the balls, at P_k, mm	0.66-0.67	0.60 -0.72
P_k ratio of MS20 and MK-8 oils	1.5	1
At 100°C		
critical oil film breakdown load P_k, kg	39	58
width of wear of the balls at P_k, mm	0.50	0.98
P_k ratio of MS-20 and MK-8 oils	1.5	1

* The kinematic viscosity of MK-8 oil at 50°C was 8.4 cs, at 100°C
the viscosity was 2.97 cs, and for MS-20 oil the values are 157
and 20.3 cs, respectively.

Investigations of the anti-wear properties of oils on a test stand with
a free overrunning shaft and on the KV-1 machine reveal (see Tables 38 and
and 39) that MK-8 oil and oils of narrow fractional composition have
identical anti-wear properties; therefore a certain reduction in the
viscosity of the latter oils does not reflect on their lubricating cap-
ability.

Domestic synthetic oils based on diesters or on pentaerythritol esters,
in comparison with petroleum oils, are characterized by higher anti-wear
properties. The P_k ratio of these oils and the MK-8 oil fluctuates within
the limits of 1.4 to 2.0.

Anti-wear Addivites

The lubricating capability of TRD oils is improved by the introduction
of anti-wear and anti-galling additives. The mechanism of the effects of
additives is reduced to the formation of films on the metal surfaces.
Compounds containing sulfur, chlorine and phosphorus are employed as
additives in TRD oils.

The active elements in the additives indicated are adsorbed on the
metallic surfaces, and entering into compounds with these surfaces at
increased temperatures and pressures form sulfide, chloride and phosphite
films [75-77]. The films prevent the appearance of a dry friction condition
and reduce wear of rubbing parts. The functions of such elements as anti-
wear agents have been widely investigated and are described in de-ail in
[78].

In introducing into petroleum oils such additives as tricrysyl phos-
phate, diphenyl pentachloride (sovol) and those containing sulfur (such as
the LNMZ-25k additive, which is a butyl ether of xanthic acids), the critical
oil film disruptive load is increased by 1.5-1.7 times.

Phosphorus additives increase the critical oil film breakdown load, but
after breakdown the film is poorly restored, which may lead to galling or
even to welding of metallic surfaces. This shortcoming is well compensated
for by additives which contain sulfur. Sulfide films are less durable, but
on the other hand are more elastic and prevent welding well. Also desirable
is a combination in additives of sulfur and chlorine. In addition to
improving the anti-wear properties of oils (the fitting of metallic parts),
sulfur catalyzes the process of the formation of a film by the additives
which contain chlorine. In this connection the coupled employment of these
additives is more effective; however, the best results are obtained [79]
with the utilization of a complex of anti-wear additives, containing
chlorine, sulfur and phosphorus (Table 42).

The introduction into a petroleum lubricant of a complex of the addi-
tives indicated (3%) improves its anti-wear properties by 1.5-2 times.

The lubricating properties of petroleum oils during extended operation
in a TRD are usually somewhat improved as a result of the accumulation of
resinous oxidation products, and also as a result of a significant increase
in viscosity associated with oil vaporization.

Tricrysyl phosphate is widely employed abroad as an additive in order to
improve the lubricating properties of synthetic oils; it is introduced in
quantities of 3-5%.

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Table 42.   The Anti-wear Properties of MS-6 Oil for the TRD
Prior to and After Introduction of Additives

Additive	Additive content, wt %	Critical load P_k kg	Diameter D_{kr} of wear trace, mn	Diameter of wear trace, mm, at loads, kg				
				25	35	45	55	65
with no additive	-	30	0.37	0.35	0.56	-	-	-
Sovol	1	40	0.37	0.32	0.35	0.66	-	-
TKF	1	40	0.35	0.30	0.32	0.62	-	-
LZ-25k	1	40	0.35	0.32	0.35	0.69	-	-
Sovol	1	55	0.35	0.29	0.32	0.34	0.35	0.70
TKF	1							
Sovol	2	55	0.35	0.30	0.31	0.33	0.35	0.65
TKF	1							
Sovol........	1	55	0.36	0.31	0.32	0.33	0.35	0.68
TKF	3							
Sovol........	2	55	0.35	0.29	0.32	0.34	0.35	0.70
LZ-25k	1							
TKF	2	55	0.36	0.30	0.31	0.32	C.36	0.69
LZ-25k	1							
Sovol	1	60	0.37	0.30	0.32	0.33	0.37	0.67
LZ-25k	2							
TKF	1	60	0.37	0.29	0.30	0.34	0.35	0.75
LZ-25k	2							
Sovol	1	70	0.37	0.29	0.30	0.34	0.35	0.70
TKF	1							
LZ-25k	1							

CHAPTER EIGHT

THE CORROSION PROPERTIES OF OILS FOR TURBOJET ENGINES

In a TRD the lubricant is in contact with metals and their alloys. The most often encountered are steel, copper, aluminum, lead (lead-coated surfaces), lead and phosphor bronze, brass, magnesium and aluminum alloys, etc. The wide assortment of metals employed in jet engines requires that a careful study be made of the corrosion properties of lubricants developed and employed.

The corrosion properties of lubricants are important indicators which characterize their behavior in a TRD at high temperatures.

A lubricant must protect engine parts and assemblies from corrosion not only during the operating process, but also during extended standing of aircraft under usual temperature conditions. The basic method of combating corrosion (aside from the application of protective films on the metallic surfaces, obtained by anodizing or oxidation, etc.) is the use of lubricants with high anticorrosion properties.

The corrosive activity of TRD lubricants is determined by the chemical composition of the oils and also by the properties of the products formed during their oxidation.

Various carboxylic acids are contained in petroleum oils, and largely in the products of their oxidation. Notwithstanding the fact that some acids (naphthenic) display weak acidic properties, they are active causes of metal corrosion, especially of nonferrous metals. In destroying metals, the naphthenic acids form soap with them, which may remain in solution in the oil or which may be precipitated. The naphthenic acid content in oil is usually insignificant, and therefore the acid number of fresh petroleum oils falls within the range 0.03-0.04 mg KOH/g. At temperatures of 30-50°C, oils of this acidity do not corrode metals; however, with an increase in operating

temperatures and an increase in acid product content, the corrosive activity of the oils increases.

At high temperatures, metals which are in contact with oil in turn have a catalytic effect on the process of oil oxidation; the most active metal is copper.

An oil sample (10 g) was oxidized in a glass beaker for three hours with a constant quantity of air (the ratio of oil and air volumes was approximately 1:1.5). The quantity of deposits was determined by filtration of the oil through a special microfilter. The results of the tests are shown in Table 43.

Table 43. The Catalytic Influence of Metals During the Oxidation of
TRD Petroleum Oils*

Oil	Oxidation temper- ture, °C	Catalyst	Quantity of deposits, %	Acid No., mg KOH/g	Viscosity at 50°C
MS-6	-	-	0.017	0.01	6.15
	175	steel	0.033	0.17	6.17
	175	copper	0.046	0.32	6.25
	200	steel	0.030	0.33	6.28
	200	copper	0.300	0.56	6.32
MK-8	-	-	0.007	0.01	7.2
	175	steel	0.005	0.41	9.31
	175	copper	0.06	0.43	9.36
	200	steel	0.040	-	-
	200	copper	0.10	-	-

* The tests were conducted according to the method of Papok and Zuseva.

The load on the engine parts exerts a significant influence on corrosion intensity. It is pointed out [60] that the higher the operating load, the greater the bearing corrosion. At high TRD turbine shaft rates of rotation (up to 20,000 rpm), even insignificant defects on the rolling bodies of the bearings, which cause corrosion, may lead to their breakage [70].

In connection with the corrosive action of TRD lubricants, it is necessary to exercise control during their production and employment.

The corrosive properties of TRD oils are determined in a Pinkevich apparatus (GOST 5162-49) on plates of lead and several other metals. This method consists of the effect on metallic plates of heated oil, a thin film of which is periodically brought to the contact with atmospheric oxygen. The corrosive activity of the oil is established by a change in the weight of the plate after 50 hr of tests in oil heated to 140°C, and is expressed in g/m^2. Sometimes the oil is tested at higher temperatures.

At temperatures above 150-160°C, the method of determining the corrosive activity in accordance with GOST 5162-49 is not suitable for low-viscosity petroleum oils due to significant vaporization during the time of the test (50-60%). Therefore during research work the corrosion properties of jet engine oils at temperatures above 160°C are determined by means of the reaction of metal plates with oil in special hermetically sealed containers of stainless steel, and also in a special device proposed by Ye. P. Bel'chikova and O. I. Zapol'ska. The latter method differs fundamentally from the GOST 5162-49 method in that the metals are subjected to the corrosive effect of oils at high temperatures with the return of condensing oil vapors. Corrosion is determined by this method in a device which consists of a glass flask having a volume of 0.75-1.0 l with a reflux condenser. The plates of the test metals are hung on glass hooks in the flask at various levels (in the liquid, in the vapor phases or at the interface of these phases). The test temperature corresponds to the temperature at which the oil is employed in an engine; the duration of the test is 200-300 hr, which is approximately equal to the period of service of the oil in a TRD without a change. To a great extent this method reflects oil operating conditions in a TRD, although this method, just as the method according to GOST 5162-49, is cumbersome and requires an extended period of time.

Oil corrosion may be determined in a shorter period of time (approximately 2 hr) on the PZZ device.

Domestic TRD petroleum oils at initial acidity values of 0.02-0.04 mg KOH/g are characterized by insignificant corrosion activity; usually they cause no corrosion to operating engine parts. The indicators of corrosion properties of these oils (GOST 5162-49), determined at 100°C on lead plates, are shown below (in g/m^2):

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MK-8	10-17*
MK-6, maximum	30
MS-6, maximum	5

* Practical data.

In the employment of MK-6 oils, creeping of lead coatings in the engines is not observed. For comparison it must be pointed out that during more intensive cleaning type MK-6 oil, obtained from Anastas'yevka crude (50% sulfuric acid) is deprived of natural oxidation inhibitors and therefore causes lead corrosion of approximately 50 g/m^2. The least corrosive activity insofar as lead is concerned is possessed by MS-6 oil; this is explained by the content in the oil of 0.2% Ionol and 0.7% sulfur, which is capable of forming a protective film of lead sulfide on the lead plates. The different corrosive properties of various batches of MK-8 oil occur as a result of the different composition of the initial crude. For the same reason separate batches of MK-8 oil also differ significantly from each other insofar as thermal oxidation stability is concerned.

An evaluation of the corrosive activity of oils on lead plates in accordance with GOST 5162-49 is not sufficient, since various metals and alloys, many of which are more sensitive to corrosion than lead are used in TRD's. Therefore in determining the corrosive activity of oils developed and investigated, especially synthetic oils, three-five metals are employed, depending on the chemical composition or the origin of the oil.

At ordinary temperatures, petroleum oils, even if in contact for an extended period of time with nonferrous metals, do not cause corrosion; therefore during storage of the engines petroleum oils do not have to be removed. Thus, tests accomplished in accordance with the condensate return method have revealed that MK-8 and MS-6 oils at room temperatures cause no corrosion to steel, copper, aluminum or their alloys for a period of 100 hr to 130 days. At increased temperatures corrosion increases to some extent: at 150°C for 100 hr corrosion on copper and lead bronze in MS-6 oil amounted to 2 g/m^2, and corrosion to aluminum D-16 and steel 45 did not exceed 1 g/m^2.

According to the author's data at 150°C (determined in accordance with GOST 5162-49) MK-8 and MK-6 oils cause no corrosion to copper, aluminum, steel, brass and lead bronze; with MS-6 oil on copper plates the increase in weight was 0.2 g/m^2, and on lead bronze plates the corrosion amounted to 0.3 g/m^2.

The corrosion activity of oils may be evaluated on the PZZ device, where the tests are conducted for two hours at 150°C, the rate of oil circulation in the system is 125 ℓ/hr and the quantity of air supplied is 50 ℓ/hr. In this case the corrosion indication on lead plates is 4-7 times higher than the determination in accordance with GOST 5162-49, which permits a clearer differentiation of TRP petroleum lubricants insofar as their corrosion activity is concerned (Table 44).

Table 44. The Results of Oil Corrosion Activity Tests with the PZZ Device*

Oil	Kinematic viscosity at 30°C, cs		Acid No. mg KOH/g		Corrosion on lead, g/m^2	Quantity of deposits, %
	Before testing	After testing	Before testing	After testing		
MK-8	8.5	12.0	0.01	3.26	136	2.1
experimental MK-8 from Anastas'-yevka crude	8.5	16.9	0.03	5.98	224	14.0
experimental MK-8 of Anastas'-yevka crude + + 0.5% Ionol	8.5	9.3	0.03	0.03	0.3	0.6
MK-6	6.1	9.2	0.03	6.49	170	3.6
MK-6 + + 1.7% Ionol	6.1	6.3	0.03	0.03	13	0.4
MS-6	6.2	6.7	0.01	1.51	26	6.2
sour crude transformer oil	8.6	10.8	0.02	3.89	26	6.8

* Data of K. K. Papok, A. P. Zarubin and G. V. Zakharova.

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The corrosive properties of petroleum oils, as noted above, are directly associated with their acidity, which increases during oxidation. Therefore the introduction into petroleum oils of antioxidant additives ahrply reduces their corrosive activity since it inhibits the development in the oils of oxidation processes (see Table 44).

Even during tests of MK-8 oil on the PZZ device under stricter conditions ([4]hr at 175°C), the introdu tion of Ionol provides sufficient anticorrosion effect: thus, 1% of Ionol reduces the oil acid number after oxidation from 4.86 to 0.22 mg KOH/g and the corrosive activity insofar as lead is concerned from 177 to 14 g/m^2.

Corrosion indicators for TRD petroleum lubricants in the USA are of the same order as those for domestic petroleum oils. Thus American petroleum oils of the 1005 and 1010 types (MIL-0-6081B specification) cause practically no corrosion of copper plates at ᴧ00°C. After tests for 168 hr at 121°C, the corrosion of copper, steel, aluminum and magnesium alloys and of cadmium-plated steel amounted to not more than ±2 g/m^2.

The corrosive activity of synthetic oils employed in the USA on the basis of various diesters at 170-260°C is higher than for petroleum oils. It has been pointed out in the literature [80] that the formation of moncesters of dibasic acids having only one free acid group is the reason for the corrosive effect of diester oils, as a result of hydrolysis. Under oil storage conditions this reaction occurs slowly, but with an increase in temperature the rate increases rapidly. Thus at 175°C diisoctyl azelate causes rapid corrosion of copper, magnesium and iron (Table 45).

Synthetic oils based on pentaerythritol esters display even more corrosive activity with respect to copper and its alloys.

In the USA tests for corrosion are usually combined with oil thermal oxidation stability determinations. With this combined method the metals simultaneously serve as oxidation catalysts.

Depending on specification requirements or on the chemical composition of the oil, corrosion-oxidation test conditions may differ. Thus according to the MIL-L-7808 specification the oxidation-corrosion test for oils based on diisoctyl sebacate are conducted at 175°C for 72 hr with an air delivery

of 5 ℓ/hr. Corrosion on copper must not exceed 0.6 g/m^2, and on magnesium, iron, aluminum and silver, not more than 0.3 g/m^2. Viscosity during oxidation may change within the limits from -5 to 15% (viscosity is determined at 37.8°C). In agreement with the requirements of the MIL-L-9236B specification, oxidation corrosion is determined at 260°C for 46 hr with an air delivery of 5 ℓ/hr. The corrosion on plates of copper, titanium, iron, aluminum and silver must not exceed ±5 g/m^2.

Table 45. The Corrosion Activity of Synthetic Oil Based on Diisoctyl Azelate

| Metal | Corrosion, g/m^2 | |
	With no additive	Specified requirements for oils with additives
copper	-56	maximum ± 4
magnesium	-204	
iron	-12	
aluminum	not available	maximum ± 2
silver	" "	

In order to evaluate the corrosive activity of oils which they have acquired under storage conditions, the American research center "Wright Field" developed an accelerated method for testing oils [81]. This method consists of storing oil in three-liter metal cans with plates of various metals at 85°C: the results obtained by this method satisfactorily coincide with the results of the extended storage of oils under field conditions. This method of accelerated oil damage during storage in accordance with the VVS [Military Air Force] requirement is included in the MIL-L-7808D specification. Maximum lead corrosion after oil storage with lead plates at 85°C for 14 and 45 days must not exceed 4.0 and 230 g/m^2, respectively.

Special anticorrosion additives are introduced into several foreign TRD synthetic oils. These include benzothiazole, mercaptobenzothiazole and and several other similar products.

CHAPTER NINE

THE EFFECT OF OILS FOR TURBOJET ENGINES ON AVIATION RUBBER

The influence of lubricants on parts manufactured from rubber (cuffs, rings, gaskets), must be minimal, since these parts cannot fulfill the sealing functions assigned to them if a change occurs in rubber quality.

The process of chemical reaction between oil and rubber depends mainly on their nature; however, temperature and the duration of their contact also exert a significant influence. If a lubricant is corrosive with respect to rubber, then in addition to a change in weight and volume associated with washing-out of the ingredients of the rubber or with rubber swelling, the following qualitative changes in rubber articles also occur:

q reduction in the tensile strength, brittleness temperature range and decreased relative expansion;

an increase in hardness and residual compression deformation;

a deterioration in resistance to frost.

As a result of high temperatures and the chemical reaction of oil, rubber cuffs and gaskets lose elasticity, become hard, brittle and may crack and disintegrate, which causes oil leakage through sealing devices.

Laboratory investigations of rubber reactions to oil are rather prolonged -- in some cases they require 400-500 hr. In foreign practice similar tests are also quite lengthy. Thus, according to the requirements of the MIL-L-7808 specification, rubber swelling tests in oil are conducted at 70°C for 168 hr[1]. Quick methods for an accelerated determination of the influence of lubricants on aviation rubber in the area of jet oils under consideration have thus far not been widely utilized.

Synthetic oils, for example, those based on diesters, pentaerythritol esters, etc. (Tables 46 and 47) have the most intensive effect on rubber; for

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[1]

such oils special types of rubber are usually developed which are resistant to these oils. Type 3825[2] (see Table 47) rubber is especially resistant to synthetic diester oil. Petroleum oils such as MK-8, MS-6, etc., show appreciable effect on rubber only at high temperatures and with an extended contact of 150-200 hr. Of the rubbers investigated, types 4410 and 9831 are quite resistant to petroleum oils; at 120-150°C no washing-out of ingredients is observed.

Insofar as the effect on rubber is concerned MK-8 and MS-6 petroleum oils are approximately identical. MS-6 oil gives satisfactory results in contact with type 3825, 3826, 4410 and 9381 types of rubber at 125-150°C for more than 200 hr (continuous effect under laboratory conditions), and also up to 500 hr with rubbers of the V-14, IRP-1078, 4410, 9831 types at 100-120°C. TRD tests have shown that domestic petroleum oils have practically no destructive effect on articles of the various types of rubber utilized in these engines.

In order to avoid oil vaporization during laboratory investigations under high-temperature conditions, the oil and rubber specimens tested are placed in hermetically sealed containers. The containers are maintained in oil thermostats.

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[2] See p. 120.

Table 46. Results of the Action of Petroleum and Synthetic Oils on Rubber for Periods of 24 and 48 hr

Oil	Type 4327 rubber		Type 3825 rubber	
	Swelling, wt %, during testing for period of			
	24 hr	48 hr	24 hr	48 hr
At 70°C				
MK-8	-1.56	-	-2.92	-3.73
MK-6	5.51	-	-1.68	-
MS-6	-3.74	-3.71	-3.86	-4.59
synthetic diester	21.3	-	1.1	-
At 100°C				
MK-8	-0.71	0.10	-3.73	-3.05
MK-6	1.17	-1.29	1.0	-
MS-6	-4.16	-4.60	-4.85	-4.74

Table 47. Results of the Effect of Petroleum and Synthetic Oils on Rubber for a Period of 240 hr at 200°C

Time, hr	Weight change, %			
	Type 4327 rubber		Type 3825 rubber	
	MK-8	Synthetic diester	MK-8	Synthetic diester
24	-1.07	3.38	-0.49	-0.07
72	-1.59	7.62	-0.62	-0.20
96	-1.96	8.62	..	-
120	-2.11	11.40	...	-
144	-2.27	12.78	-1.80	-0.19
168	-2.29	-	-	-0.18
192	-2.39	15.30	-	-
216	-2.41	15.40	-	-
240	-2.45	16.17	-2.10	-0.19

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Footnotes

1. To p.117.   Swelling of synthetic rubber must not exceed 12-35%.

2. To p.118.   All rubber discussed in this chapter is manufactured under MRTU [Interrepublic Technical Specification] 5-38-1166-64.

CHAPTER TEN

THE FOAMABILITY OF OILS FOR TURBOJET ENGINES

The Causes of Foaming

The high circulation multiplicity factor of a lubricant in a TRD oil system leads to the intensive mixture of oil with air. Oil flowing from lubrication points contains up to 30-40% air. Therefore during the spraying of oil in gear drive housings, foam is formed: foaming of oil occurs also at the oil exit from oil knjector jets. Corresponding conditions for foam formation are also formed in the oil tank, where the pressure is always lower than in the entire engine oil system.

Oil foaming causes the operation of the engine oil system to deteriorate: the heat capacity and the thermal conductivity of the oil decrease; here cooling of rubbing engine parts also deteriorates; the quantity of oil delivered to lubrication points decreases in connection with the increase in oil volume due to foaming. Due to the high volume of foaming oil at the output of lubrication points, the output of TRD evacuating pumps must be higher than the pumps which deliver oil after the air separator to the oil system pressure line. Simultaneously with the reduction in the output of oil pumps, oil consumption is increased as a result of throwing off foam with air through the engine breathing system.

Oil foaming during TRD operation is unavoidable; in this connection the oil must be characterized by a minimal capability for foam formation.

The foaming of oil depends on its chemical nature. Of the physical characteristics of a lubricant, the most influential on foam formation are density, surface tension and the viscosity-elastic properties of the surface layers.

It is believed that with an increase in temperature the foaming of oils has a tendency to fall; but for several oils foaming first increases with an increase in temperature, and then falls due to a decrease in oil viscosity

and foam stability, since the durability of the oil films is reduced. A reduction in the pressure of the surrounding air leads to an increase in foam formation in oils. The foaming of oils is also influenced by the additives introduced into the oils, which in a number of cases are surface-active substances and are adsorbed on the oil films. There are indications in literature that in a number of cases the foamability of oils is caused by the addition of anti-wear additives [82], viscosity additives [83], etc. Traces of water usually increase sharply the tendency of oils toward foam formation

The Methods of Evaluating Foamability

The foamability of oils is evaluated by a number of methods. The work methods and device suggested by L. V. Zhirnova are the most widely employed. Foam is formed in this device during the free fall of a jet of oil in a zone of reduced pressure. According to this method 100 ml of test oil is placed in flask (1) (Figure 33) and is heated to a specified temperature. The required vacuum is created in calibrated cylinder (2) by means of a vacuum pump; the vacuum corresponds to a height above sea level of 10,000 m (a residual pressure of 198 mm Hg). Oil from the atmospheric pressure zone (flask (1)) is delivered through an open valve to the zone of reduced pressure (cylinder (2)), where it falls freely in a thin jet, which forms foam. The foamability of oils according to this method is characterized by a foam coefficient -- the ratio of the height of a layer of foamy oil to the height of a layer of oil after the foam has been destroyed. The foamability of the oil and the durability of the foam is also judged by the duration of foam existence in cylinder (2).

The foamability of oils for TRD's may also be determined in Yu. Mamedaleyev's device, where the oil is subject to foaming in a measuring cylinder bv means of bubbling air through the oil. The following design for this device is provided in accordance with an improved modification for this method. A glass cylinder with a volume of one liter is placed in a water thermostat, in which a quantity of test oil (190 ml) is placed; a bubbler is then introduced in order to deliver air to the oil. The bubbler is a glass tube with filter SP-2 sealed at the end of the tube in order to disperse the air. The quantity of dehumidified air which passes from the blower to the cylinder is measured by a flowmeter. The foamability of the oil is

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determined in five minutes at an air delivery rate of 40 ℓ/hr and at temperatures of 20 and 80°C. These specially selected conditions are the optimum ones for an evaluation of the foamability of synthetic and petroleum TRD domestic oils and must be strictly maintained. The foaming tendency of the oils is evaluated just as in the preceding method, in accordance with the height of the foam layer formed and in accordance with its duration after air delivery has ceased.
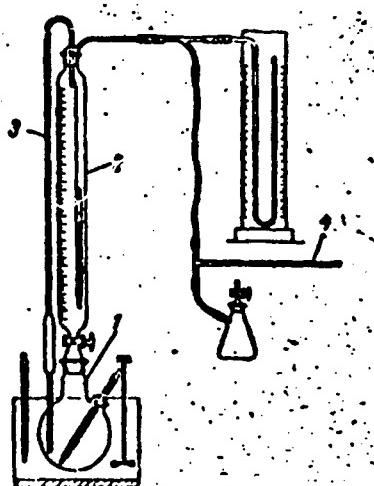
Figure 33. Diagram of a device for the determination of oil foamability: 1, Flask; 2, Cylinder; 3, Pipe for oil delivery to cylinder; 4, Pipe to vacuum pump

Investigations of the Foam-Forming Capability by Laboratory Methods

The basic external factors which influence the foamability of oil in an engine are oil temperature and pressure on the surface (the flight level of the aircraft). Investigations of the foamability of MK-8 oil, conducted by L. V. Zhirnova in accordance with the oil jet delivery method, revealed that that with an increase in temperature the tendency of oil toward the formation of foam is reduced (Figure 34); simultaneously the period of existence of the foam, or its durability, is reduced.

With a reduction in the pressure on the oil, foamability increases; however, the life of the foam is curtailed, which is apparent from the following data (in seconds):

Pressure on the oil mm Hg	Foam duration at 100°C, sec
198	600
90	90
40	90
19	60

At 200°C the duration of foam existence, independent of pressure, does not exceed several seconds.

According to the data of L. I. Saranchuk and N. F. Ronzhina [4], with an increased vacuum over the oil to a value corresponding to an aircraft altitude of 20 km, the foam coefficient of the MK-8 oil reaches 2.2 (Table 48).
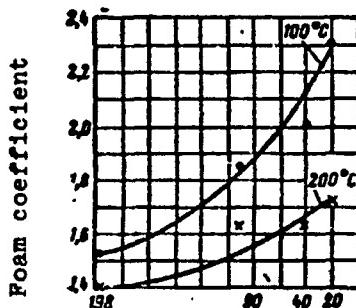
Figure 34. The foamability of MK-8 oil at various temperatures as a function of air pressure

When the temperature is increased from 100 to 200°C, foam life is reduced from 20-25 to 1-5 sec [4].

These same regularities were also confirmed by the author during a study of oil foamability by means of bubbling air through the oil in a measuring cylinder (Table 49)[1].

It is apparent from the data in Table 49 that MK-8, MK-6 and MS-6 petroleum oils are characterized by relatively low foamability; the durability of the foam at a temperature near the application temperature in an engine (80°C) is not significant. With extended operation of these oils in a

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[1]See p. 130

TRD, no disruption in the operation of the oil system due to oil foaming occurs. A certain increase in the tendency toward foam formation of MK-6 oil at 20°C is explained by the content in this oil of a significant quantity of aromatic hydrocarbons; however, at 80°C they no longer have any influence on oil foam formation.

Table 48. The Influence of Temperature and Pressure Over the Surface on the Foamability of MK-8 Oil

Residual pressure in device mm hg	Height above sea level corresponding to this pressure, km	Oil temperature °C	Foam coefficient
198	10	100	1.5
198	10	200	1.1
90	15	100	1.8
90	15	200	1.5
41	20	100	2.6
41	20	200	2.2

Synthetic oils based on diesters and pentaerythritol esters do not foam under test conditions at temperatures up to 80°C.

Investigations of the foam-producing tendencies of TRD oils, accomplished by the author at various temperatures and pressures and in accordance with the oil jet delivery method[2], have revealed a rather complex dependence of oil foamability on temperature (Table 50).

Thus for petroleum oils the foaming capability increases with an increase in temperature, and reaches a maximum at 50°C. During a subsequent increase in temperature, the foamability of petroleum oils is reduced and at a temperature of approximately 150°C it has the same value as at 25°C.

For the synthetic oils investigated, the maximum foaming is observed at 100°C; this is reduced with a subsequent increase in temperature. It is

apparent that foaming of synthetic oils is insignificant and has practically
no influence on the operation of the TRD oil system.

Table 49. The Foamability of TRD Oils Determined in Accordance with the
Method of Bubbling Air Through the Oil

Oil	Height of layer mm		Duration of existence	
	At 20°C	At 80°C	At 20°C min	At 80°C sec
MK-8	50	25	6	45
MK-6	118	26	33	28
MS-6	20	10	4	15
Synthetic oil based on diesters	did not form		–	–
Synthetic oil based on pentaerythritol esters ....did not form			–	–

The tendency toward foaming of MK-6 oil (just as during investigations
in accordance with the air bubbling method) is somewhat greater than MK-8 and
MS-6 oils.

The petroleum oils investigated have viscosities which are quite close
together; therefore it is impossible to establish a relationship between
their viscosity and foaming capacity, although this would present some
interest in connection with the tendencies to employ in the future higher
viscosity oils at high temperatures. On this problem there is no single
opinion among researchers. Shteynbakh [82, 83] believes that the lower the
viscosity the higher the tendency toward foaming. Kele [84] expresses the
opposite point of view. Kichkin [85] investigated oils[3] with viscosities
from 17.5 to 3250 cs at 20°C and came to the conclusion that there is a
complex relationship between the foam-producing tendency of oil and its
viscosity. Initially the tendency toward foaming decreases with an increase
in viscosity, then it increases and attains a maximum at a viscosity of
300 cs, and with a subsequent increase in viscosity again decreases. With an
increase in viscosity the life span of the foam increases, and with a temper-
ature increase, it decreases.

During tests of MS-6 and MK-8 oils in accordance with Kichkin's method,
the height of the foam layer was 40 and 50 mm, respectively, and the life of

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[3]See p. 130

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the foam was 1 and 2.5 min. With an increase in temperature to 100°C, the foam formation of petroleum oils increased. Thus with an increase in temperature from 20 to 100°C, the foamability of MK-8 oil (the height of the foam layer) increased from 50 to 300 mm or by six times, which contradicts the data cited previously on this problem.

Table 50. The Foaming Capability of TRD Oils, Determined in Accordance with Jet Delivery Method

Oil pressure over oil in device, mm Hg	Oil foam coefficient				
	MK-8	MK-6	MS-6	Based on diesters	Based on pentaerythritol esters
At 25°C					
1.98	1.05	1.10	1.09	1.00	1.03
90	1.09	1.20	1.21	1.01	1.07
18	1.52	1.46	1.70	1.02	1.08
At 50°C					
198	1.12	1.32	1.13	1.02	1.05
90	1.26	1.52	1.27	1.03	1.09
18	1.87	2.02	1.74	1.05	1.11
At 100°C					
198	1.14	1.30	1.15	1.05	1.07
90	1.41	1.41	1.27	1.07	1.09
18	1.49	1.49	1.40	1.09	1.14
At 150°C					
198	1.11	1.14	1.10	1.05	1.06
90	-	1.21	1.18	1.08	1.08
18	1.37	1.27	1.23	1.09	1.10
At 200°C					
198	1.07	1.09	1.08	1.05	1.05
90	1.14	1.12	1.10	1.06	1.07
18	1.16	1.13	1.11	1.08	1.12

In the USA and England, the foamability of TRD oils is determined in accordance with the ASTM D-892 method (which corresponds to the English IP146/55 method), which in technical content is close to the method described above of determining oil foamability in a cylinder by the air bubbling method.

According to the ASTM D-892 method, 190 ml of oil is placed in a cylinder having a volume of 1 l, of strictly determined geometric dimensions

and air is passed through the oil at the rate of 94 ± 5 mℓ/min at 23.9, then at 99.3 and again at 23.9°C; for each of these temperatures a fresh portion of oil is taken and air is delivered each time for 5 min. After this the haight of the foam layer and the duration of i^{...} disintegration are established.

The evaluation of oil foamability in accordance with this method is included in the MIL-L-7808(A-E): the MIL-L-9236 (A and B); the MIL-L-27502; Allison-359 and other specifications. Thus in the MIL-L-7808E specification for Castrol-98 synthetic oil, the following oil foamability indicators are shown:

Temperature	Foam height, mm, maximum	Duration of foam existence, min, maximum,
23.9	40	0.5
99.3	10	0.2
23.9	50	0.6

For a number of foreign synthetic oils the following requirements have been introduced: the height of the foam according to the ASTM D-892 method at 99.3°C must not exceed 25 mm, and at 23.9°C, not more than 100 mm[4] [86, 87]. The most effective method of combating oil foaming during engine operation is the introduction into the oil of special antifoaming addi-tives — organosilicon compounds, including several alkyl siloxanes and silicones. Silicones are characterized by the fact that they possess low surface tension and display insignificant solubility in oils. It has been shown [88] that with a low concentration of substances having lower surface tension than oil, foam formation is noticeably reduced in a case when the solution is in the form of two phases and the solute is thinly dispersed in the oil. The quenching of foam by means of silicones makes use of this effect.

Since with an increase of the solubility of silicones in oils their antifoaming effect decreases, silicones are usually employed as antifoaming additives which have comparatively high viscosities — from 1000 to 6000 cs at 25°C and molecular weights from 20,000 to 50,000.

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[4]See p. 130

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Antifoaming additives are introduced into oils in small quantities, not more than 0.001-0.0001%, which also depends on their poor solubility in petroleum oils. The silicone liquid PMS-200-A is most often employed as a defoamer for petroleum oils.

With the introduction of 0.001% of the antifoaming silicon additive S to MK-8 oil (according to data furnished by G. I. Kichkin), the height of the foam layer at 20°C is reduced from 50 to 20 mm, which indicates the high effectiveness of additives of this type.

Footnotes

1. To p.124. The work was accomplished jointly with I. V. Golovistikov and V. A. Nikolayeva.

2. To p.125. The work was accomplished jointly with G. I. Krylova.

3. To p.126. Oil foamability is determined in a glass cylinder with the delivery of nitrogen at the rate of 4 ℓ/min through 100 mℓ of oil.

4. To p.128. Duration of foam existence must not exceed 5, 3 and 5 min.

CHAPTER ELEVEN

THE CHEMICAL GROUP COMPOSITION OF PETROLEUM OILS FOR TURBOJET ENGINES

Many important operating properties of TRD petroleum oils, such as thermal oxidation stability, viscosity-temperature characteristics, etc., are determined by the chemical group composition and also by the structural group composition of the oils. This is clearly seen in a comparison, for example, of the physicochemical indicators for MK-8 oil (GOST 6457-66) from Balakhany crude with experimental MK-8 oil (specimen 1) from Troitsko-Anastas'yevka crude (Table 51).

These oils which have similar boiling ranges (300-400°C), are obtained at the usual cleaning depth of distillates by sulfuric acid (6-9%) and have identical viscosities at 50°C. Nevertheless MK-8 oil (specimen 1) from Troitsko-Anastas'yevka crude in comparison with MK-8 oil in accordance with GOST 6457-56 has a higher viscosity at -40°C, a poorer viscosity ratio and increased density. Its viscosity at -40°C increases sharply after vaporization. Such a significant difference in physicochemical properties of these oils is caused by their dissimilar chemical group composition.

Having changed the chemical group composition of petroleum oils by means of an appropriate cleaning of their distillates, we may obtain significant changes in the basic physicochemical properties of the oils. Therefore a study of the chemical group composition of petroleum oils and its relationship to the physicochemical characteristics of the oils presents considerable interest.

The chemical group composition of petroleum oils for TRD's is determined by the use of separation by an adsorbent. A single, unified technique for this determination does not exist; the most widely employed methos is as follows. A sample of test oil is dissolved in isooctane (at a ratio of 1:3, respectively), and the solution is poured into an adsorption column, filled with coarse-grained, activated silica gel of the ASK type. The quantity of

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Table 51. The Physicochemical Properties of TRD Petroleum Oils*

Indicator	MK-8 from Balakhany crude (GOST 6457-66, cleanable with 9% sulfuric acid)	MK-8 from Troitsko-Anastas'yevka crude cleaned with sulfuric acid 6% (specimen 1)	MK-8 from Troitsko-Anastas'yevka crude cleaned with sulfuric acid 6% (specimen 2)	Transformer oil from Tuymazy crude solvent refining	MS-8 Zhirnovsk crude solvent refining	Oil of narrow fraction composition — Experimental oil of: MK-6 of Balakhany crude cleaned with 9% sulfuric acid	MK-8 Troitsko-Anastas'yevka crude cleaned with 6% sulfuric acid	MS-6 from Tuymazy crude solvent refining
Kinematic viscosity								
At 50°C	8.8	8.7	8.7	8.5	9.2	6.4	6.1	6.1
At 20°C	28.3	29.3	28.4	27.3	29.4	10.0	17.4	16.3
at -40°C before vaporization	8960**	12700	5900	4600	4100	2370	2550	1500
after vaporization	19150**	35000	16800	-	6830	4730	3000	1700
Ratio of viscosities at 20°C and 50°C	58.1	73.3	59.3	48.5	51.2	39.5	42.7	28.1
density ρ₄²⁰	0.875	0.895	0.884	0.853	0.856	0.870	0.880	0.843
stability in accordance with GOST 981-56 deposits after oxidation %	0.10	0.05	0.08	0.14	0.10	0.10	0.08	none
acid number, mg KOH/g	0.35	0.20	1.2	0.51	0.80	0.39	0.34	0.06
Corrosion on lead plates g/m² at 100°C for 50 hr	10**	50.5	-	-	-	10	30	5

* In all cases the oils were cleaned with 95-97% sulfuric acid. Solvent-cleaned oils were obtained at a phenol to base ratio of 2:1.
** Factual data

silica gel chosen is based on a calculation of 30 g for each 50 g of oil being separated. After a 12-hr holding time in the column, the methane-naphthenic and light aromatic hydrocarbons are successively desorbed from the silica gel by the isooctane, and the remaining aromatic hydrocarbons by benzene, and the resins, by an alcohol-benzene mixture. The clearness of the separation of methane-naphthenic hydrocarbons from the aromatic hydrocarbons is controlled by means of a formalith reaction.

The groups of hydrocarbons desorbed from silica gel are arbitrarily sorted into the following ranges of refractive index values:

methane-naphthenic hydrocarbons	1.46-1.49
light aromatic hydrocarbons	1.49-1.52
medium aromatic hydrocarbons	1.52 and above

Oils obtained from different petroleum bases differ sharply among themselves in chemical group composition (Table 52) [89].

Distillates and oils obtained from highly aromatized Troitsko-Anastas'yevka crude (specimens 2, 5-7) especially are separated out by aromatic hydrocarbon content. Thus in an MK-8 oil distillate based on this crude (specimen 5) aromatic hydrocarbons are twice as high as in the MK-8 oil, based on Balakhany crude (specimen 1). After the cleaning of specimen 5 by sulfuric acid (6%), the chemical group composition of this specimen showed little change (specimen 6), since here mainly the basic resins are extracted, and the aromatic hydrocarbons are only partially affected. For this reason the oil (specimen 6) has a very high aromatic hydrocarbon content (37.5%) in comparison with all of the oils obtained from other crude. Only with very deep cleaning of specimen 5 with sulfuric acid does the content of aromatic hydrocarbons decrease to 26% (specimen 7) and thus become comparable with the content in oils from other crudes.

The aromatic hydrocarbons exert a very significant influence on the flatness of the viscosity-temperature curve, on the thermal oxidation stability and on several other important operating properties of oils. The influence of the aromatic hydrocarbon content on the properties of the oils indicated is seen very clearly in comparison with the quality of oil specimens 6 and 7, obtained from Troitsko-Anastas'yevka crude. MK-8 oil (specimen 1) from Troitsko-Anastas'yevka crude, which contains the largest quantity of aromatic hydrocarbons, has the worst viscosity-temperature

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indicators (the viscosity at -40°C, viscosity ratio) and the highest refractive index (see Tables 51 and 53). These indicators improve and attain levels established for MK-8 oil from Balakhany crude (GOST 6457-66) in proportion to the sulfuric-acid cleaning of the MK-8 distillate from Troitsko-Anastas'yevka crude.

Table 52. The Chemical Group Composition (in %) of Type MK-8 Oils Obtained from Various Crudes

Specimen numbers	Oil	Methane naphthenic hydrocarbons	Aromatic hydrocarbons				Resins	Losses
			Light	Medium	Heavy	Total		
1	MK-8 from Balakhany crude	75.3	8.1	8,1	7.0	23.2	0.9	0.6
2	MK-6 from Troitsko-anastas'yevka crude	62.5	8.8	17.2	9.8	35.8	0.9	0.8
3	MS-6 from Tuymazy crude	81.4	12.1	2.3	3.6	18.0	0.4	0.2
4	Transformer oil from Tuymazy crude	76.0	13.7	3.6	3.9	21.2	0.6	2.2
		Experimental oils						
5	MK-8 distillate from Troitsko-Anastas'yevka crude	51.6	12.6	25.2	6.4	44.2	3.5	0.7
6	MK-8 from a distillate cleaned with 6% sulfuric acid	59.5	12.6	18.7	6.2	37.5	2.4	0.6
7	MK-8 from a distillate cleaned with 50% sulfuric acid	72.6	10.2	11.3	4.6	26.1	0.4	0.9
8	MS-8 from Zhirnovsk crude	84.9	12.1	–	1.7	13.8	–	0.3
9	MS-6 from Zhirnovsk crude	88.5	7.6	–	1.5	9.1	0.5	1.9
10	MK-6 from Balakhany crude	76.1	5.4	9.0	9.0	23.8	0.4	0.1

In oils from Tumazy, Balakhany and Zhirnovsk crudes (see table 52), the content of aromatic hydrocarbons is significantly less (9-24%) than in oils from Troitsko-Anastas'yevka crude. Basically their physicochemical indicators satisfy the requirements of GOST 6457-66 for MK-8 oil.

For oils obtained from Tuymazy and Zhirnovsk crudes by means of solvent refining (see Table 52, specimens 3, 4, 8 and 9), a high methane-naphthenic hydrocarbon content is characteristic; therefore these oils are distinguished from oils based on Troitsko-Anastas'yevka and Balakhany crudes by better viscosity-temperature properties, much lower refractive indexes and densities.

Oils from various crudes differ from each other not only by the total content of light, medium and heavy aromatic hydrocarbons, but also in their quantitative proportion. The structural characteristics of aromatic and methane-naphthenic hydrocarbons contained in oils are a significant factor. The structure of hydrocarbon molecules determines their physicochemical properties. The content of the individual structural hydrocarbon molecular elements is determined by the ring analysis method.

The Physicochemical and Ring Analysis of Methane-Naphthenic and Aromatic Hydrocarbons

The extremely widely employed Van Ness and Van Westen method [90] permits us to characterize the so-called average molecule of the hydrocarbon under investigation in accordance with the refractive index n_D^{20}, the molecular weight M and density ρ_4^{20}. It is possible by means of this method to determine the number of aromatic and naphthenic rings in an average hydrocarbon molecule, and also the carbon content in the ring structures and side chains. In conjunction with the results of the determination of the chemical group composition, the data obtained during investigations using the Van Ness and Van Westen method make it possible to evaluate qualitatively the structure of average molecules which make up the groups of hydrocarbons under investigation.

Table 53. The Physicochemical Properties and Ring Analysis Data of Hydrocarbons Fractions Separated from Type MK-8 Oils

Oils and Fractions	Refractive index n_D^{20}	Density ρ_4^{20}	Molecular weight	Specific dispersion $\dfrac{n_3 \quad n_c}{\rho}$	Sulfur content %
MK-8 distillate from Troitsko-Anastas'yevka crude					
methane-naphthenic.....	1.4723	0.8625	297	104	-
aromatic isooctane	1.4948	0.8986	281	116	-
"	1.5028	0.9097	269	125	-
"	1.5169	0.9286	258	138	-
"	1.5286	0.9441	259	151	-
"	1.5360	0.9559	252	159	-
"	1.5460	0.9671	243	171	-
"	1.5541	0.9761	237	183	-
"	1.5650	0.9873	235	197	-
"	1.5750	0.9940	222	214	-
"	1.5862	1.0067	221	224	-
"	1.5954	1.0156	216	245	-
"	1.6130	1.0377	209	258	-
aromatic benzene fractions	1.6140	1.0455	228	256	-
MK-8 fromTroitsko-Anastas'yevka crude, cleaned by 50% H_2SO_4					
methane-naphthenic aromatic isooctane fractions	1.4709	0.8592	276	98	-
	1.4910	0.8921	277	116	-
"	1.5050	0.9107	274	130	-
"	1.5148	0.9243	273	137	-
"	1.5258	0.9424	256	147	-
"	1.5365	0.9549	255	159	-
"	1.5459	0.9682	258	169	-
"	1.5631	0.9825	247	199	-
MK-6 from Troitsko-Anastas'yevka crude methane-naphthenic aromatic isooctane fractions	1.4681	0.8532	261	98	-
	1.4958	0.8957	267	123	
"	1.5124	0.9199	248	138	-
"	1.5230	0.9360	237	147	-
"	1.5350	0.9513	239	158	-
"	1.5444	0.9626	238	170	-
"	1.5705	0.9862	218	215	-

Table 53. Continued

According to Van Ness & Van Westen						According to Hazelwood					
Number of rings			Carbon content in structures, %			Number of rings			Carbon content in structures, %		
Total K_0	Aromatic K_a	Naphthenic C_n	Aromatic C_a	Naphthenic C_n	Paraffin C_p	Total K_0	Aromatic K_a	Naphthenic K_n	Aromatic C_a	Naphthenic C_n	Paraffin C_p
2.0	0	2.0	0	45.1	54.9	-	-	-	-	-	-
2.4	0.5	1.9	14.0	42.3	43.7	2.0	0.7	1.3	23.9	25.9	50.2
2.5	0.6	1.9	18.7	41.3	40.0	2.1	0.8	1.3	27.0	25.9	47.1
2.5	0.8	1.7	26.0	37.8	36.2	2.3	1.0	1.3	32.9	27.9	39.9
2.6	1.0	1.6	32.1	33.7	34.1	2.5	1.1	1.4	34.2	29.8	36.0
2.7	1.1	1.6	36.9	33.2	29.9	2.6	1.2	1.4	37.3	30.7	32.0
2.7	1.3	1.4	41.7	29.6	28.7	2.7	1.4	1.3	41.8	30.5	27.7
2.6	1.4	1.2	47.0	25.4	27.6	2.7	1.5	1.2	48.9	25.0	26.1
2.6	1.6	1.0	54.1	25.2	27.7	2.8	1.6	1.2	48.7	27.8	23.5
2.4	1.8	0.6	62.9	8.4	28.7	2.8	1.8	1.0	56.3	24.4	19.3
2.1	2.1	-	73.9	-	36.4	2.9	1.9	1.0	58.9	24.5	16.6
2.3	2.1	0.2	76.1	-	28.2	2.9	2.0	0.9	62.5	22.6	14.9
2.4	2.3	0.1	86.2	-	24.8	3.1	2.2	0.9	69.1	23.0	7.9
2.7	2.4	0.3	82.5	-	23.1	3.4	2.3	1.1	66.0	25.9	8.1
1.9	0	1.9	0	46.7	53.3	-	-	-	-	-	-
2.3	0.4	1.9	13.0	42.2	44.8	1.8	0.6	1.2	22.2	24.3	53.5
2.4	0.7	1.7	20.3	38.2	41.5	2.1	0.8	1.3	26.5	26.4	47.1
2.5	0.8	1.7	25.0	35.8	39.2	2.4	1.0	1.4	30.6	28.4	41.0
2.5	0.9	1.7	29.0	46.2	34.8	2.5	1.1	1.4	34.7	29.3	36.0
2.7	1.2	1.5	36.1	31.9	32.0	2.6	1.3	1.3	38.1	29.4	32.5
2.8	1.3	1.5	40.4	29.6	30.0	2.8	1.4	1.4	40.6	29.9	29.5
2.6	1.7	0.9	53.3	14.7	32.0	2.8	1.7	1.1	48.6	24.3	27.1
3.1	2.2	0.9	64.1	7.0	35.9	3.6	2.2	1.4	53.0	27.5	19.5
1.7	0	1.7	0.9	45.5	53.6	-	-	-	-	-	-
2.2	0.6	1.6	16.9	38.3	44.8	1.8	0.7	1.1	25.1	23.1	51.8
2.3	0.8	1.5	25.9	36.6	37.5	2.1	0.9	1.2	31.4	26.9	41.7
2.4	1.0	1.4	30.8	36.7	32.5	2.3	1.0	1.3	38.9	26.6	34.5
2.5	1.1	1.4	37.3	31.7	31.0	2.4	1.2	1.2	39.2	30.7	33.1
2.5	1.3	1.2	42.3	28.1	29.6	2.6	1.3	1.3	41.6	30.0	28.4
2.3	1.7	0.6	61.6	8.2	30.2	2.6	1.7	0.9	55.1	22.4	22.5

Table 53. continued

Oil and Fractions	Refract- ive index n_D^{20}	Density ρ_4^{20}	Molecular weight	Specific dispersions $\dfrac{n_3 \quad n_c}{\rho}$	Sulfur con- tent %
aromatic isooctane fractions	1.5398	1.0164	213	219	-
aromatic benzene fractions	1.5993	1.0268	207	245	-
MK-8 from Balakhany crude					
methane-naphthenic	1.4696	0.8586	288	100	-
aromatic isooctane fractions	1.5013	0.9031	278	130	-
"	1.5150	0.9271	277	139	-
"	1.5277	0.9484	257	149	-
"	1.5399	0.9655	247	159	-
"	1.5451	0.9713	247	168	-
"	1.5600	0.9823	239	195	-
aromatic benzene fractions...............	1.6051	1.0299	236	257	-
MS-6 from Tuymazy crude					
methane-naphthenic	1.4626	0.8384	286	98	none
aromatic isooctane fractions	1.4951	0.8872	269	127	0.5
"	1.5055	0.9032	266	139	0.7
'	1.5161	0.9217	257	149	1.4
"	1.5371	0.9519	241	173	3.1
aromatic benzene fractions	1.5522	0.9872	230	185	6.0
transformer oil from Tuymazy crude					
methane-naphthenic	1.4650	0.8435	322	98	none
aromatic isooctane fractions	1.4867	0.8806	321	122	0.4
"	1.4968	0.8906	316	128	0.5
"	1.5039	0.9007	308	135	0.78
"	1.5161	0.9232	289	142	1.55
"	1.5219	0.9374	285	150	2.33
"	1.5135	0.9628	267	177	3.1
aromatic benzene fractions	1.5425	0.9711	284	167	6.0

Table 53. continued

According to Van Ness & Van Westen						According to Hazelwood					
Number of rings			Carbon content in structures %			Number of rings			Carbon content in structures, %		
Total K_0	Aromatic K_a	Naphthenic C_n	Aromatic C_a	Naphthenic C_n	Paraffin C_p	Total K_0	Aromatic K_a	Naphthenic K_n	Aromatic C_a	Naphthenic C_n	Paraffin C_p
2.4	2.0	0.4	74.2	o.2	25.6	2.9	2.0	0.9	63.3	22.8	13.9
2.5	2.0	0.5	76.3	3.0	20.7	3.0	2.0	1.0	67.5	21.0	11.5
1.9	0	1.9	0	45.9	54.1	-	-	-	-	-	-
2.3	0.6	1.7	19.1	34.7	45.2	2.0	0.8	1.2	26.1	24.1	49.8
2.6	0.8	1.8	23.7	38.4	37.9	2.3	1.0	1.3	30.7	25.6	43.7
2.8	1.0	1.8	29.2	41.6	29.2	2.6	1.1	1.5	34.4	32.3	33.3
2.9	1.1	1.8	36.0	40.0	24.0	2.7	1.2	1.5	37.9	33.5	28.6
2.9	1.2	1.7	38.6	36.7	24.7	2.8	1.3	1.5	40.0	33.3	26.7
2.6	1.5	1.1	50.6	21.5	27.9	2.8	1.6	1.2	48.0	27.4	24.6
2.5	2.4	0.1	79	-	29.3	3.3	2.3	1.0	64.0	22.9	13.1
1.4	0	1.4	0	35.4	64.6	-	-	-	-	-	-
1.8	0.7	1.1	19.8	27.5	52.7	1.7	0.8	0.9	27.0	20.8	52.2
2.0	0.8	1.2	24.2	26.7	49.1	1.9	0.9	1.0	29.3	20.9	49.8
2.0	0.9	1.1	28.1	27.0	44.9	2.1	1.0	1.1	32.5	23.8	43.7
2.0	1.2	0.8	38.7	29.3	32.0	2.5	1.3	1.2	41.1	27.4	31.5
2.0	1.2	0.8	40.7	26.2	33.1	2.9	1.3	1.6	43.0	38.2	18.8
1.5	0	1.5	0	34.0	66.0	-	-	-	-	-	-
1.9	0.5	1.4	13.5	29.4	57.1	1.7	0.7	1.0	21.0	17.5	61.5
1.9	0.7	1.2	18.1	26.1	55.8	1.8	0.9	0.9	24.8	15.9	59.3
2.0	0.8	1.2	21.7	22.9	55.4	2.0	1.0	1.0	27.3	18.1	54.6
2.1	0.9	1.2	26.0	25.7	48.3	2.3	1.1	1.2	30.7	23.1	46.2
2.2	1.0	1.2	29.5	29.5	46.0	2.5	1.2	1.3	33.0	25.3	41.7
2.1	1.3	0.8	39.5	22.2	42.3	2.8	1.4	1.4	39.2	28.8	32.0
2.0	1.2	0.8	34.0	20.5	45.5	3.1	1.3	1.8	35.0	35.1	29.9

Notwithstanding a certain arbitrariness in this method, developed in conformity with oil concentrates, it does permit us to obtain fully comparable results. However, in an alaysis of aromatic fractions it is less accurate, and in this case the Hazelwood [91] method is additionally employed, by means of which we may obtain good results for aromatic hydrocarbons.

Naturally, the better the adsorption separation of hydrocarbon fractions by silica gel, the more accurate the results of their ring analysis. Therefore the aromatic hydrocarbons, having undergone adsorption separation, were again subjected to chromatographic separation by silica gel in small columns. The aromatic fractions were desorbed from silica gel in such a manner that the refractive index of each successive fraction differed from the preceding fraction by not more than 0.01.

On the basis of the results of physicochemical and ring analyses of groups of hydrocarbons (Table 53) released from petroleum oils by the adsorption separation method, it is possible to make the following conclusions, which are of particular interest.

All of the methane-naphthenic hydrccarbons, released from oils of different origins, have similar physicochemical properties: density, refractive index, molecular weight and specific dispersion. They are also similar in ring composition: their average molecule contains from 1.7 to 2.0 naphthenic rings. Methane-naphthenic hydrocarbons from sour crude are an exception; here lower refractive indexes and densities are characteristic. Their average molecule contains only 1.4 naphthene rings and has long paraffin side chains, which contains up to 65% of the hydrocarbon of the entire molecule (and 54% for methane-naphthenes from other raw material). The structural characteristics indicated for methane-naphthenic hydrocarbons contained in oils from sour crude exert a positive influence on the flatness of the viscosity-temperature curve of these oils.

The first aromatic fractions of all oils desorbed by isooctane are characterized by low density, high molecular weight and low specific dispersion. An average molecule of these aromatic hydrocarbons contains the least number of rings, in comparison with all other aromatic hydrocarbons; here naphthenic rings and long paraffin side chains predominate. On the basis of

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these data it is possible to conclude that structurally the first aromatic fractions are transient ones from the methane-naphthenic to the aromatic hydrocarbons. For all successive aromatic fractions, an increase in the refractive index is accompanied by an increase in density and specific dispersion, but the molecular weight decreases. The value of these indicators for the same fractions, separated from different crudes, in practically the same.

In proportion to the selection of fractions, the number of rings which characterize the average molecule increases and the length of the paraffin chains decreases. The ratio between the aromatic and naphthenic rings changes toward the aromatic, and their number increases. In the aromatic fractions having a refractive index greater than 1.54, the aromatic rings already predominate in the average molecule. It follows from this that as the density, specific dispersion and refractive index of desorbed aromatic fractions increase, the degree of their aromatization is also increased.

According to the refractive index (more than 1.54) and the specific dispersion (more than 160) it is possible to conclude that mono- and bicyclic aromatic hydrocarbons are contained in the oils under investigation. The content of these hydrocarbons in oils is not identical. Dicyclic hydrocarbons are contained most of all in oil from Troitsko-Anastas'yevka crude and least of all in oil from sour crudes. Tricyclic aromatic hydrocarbons (having a specific dispersion above 250 and a refractive index above 1.59) are contained only in a distillate of Troitsko-Anastas'yevka crude. It is the high content of dicyclic aromatic hydrocarbons and the presence of tricyclic aromatic hydrocarbons in the oil from Troitsko-Anastas'yevka crude which is responsible for its poor low-temperature properties.

The aromatic fraction sorbed by benzene for all crudes except sour ones is characterized in comparison with other aromatic fractions by the highest refractive index (1.59-1.61) and specific dispersion (to 258), by a density above unity and by the lowest molecular weight. The average molecule of these aromatic hydrocarbons has the largest number of rings, mainly aromatic, and short side chains.

The aromatic hydrocarbons contained in oils from sour crude, in comparison with the aromatic hydrocarbons from other raw material, have an

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improved nature, i.e. a relatively low refractive index, low density (not more than 0.9872) and a specific dispersion of 167-185. In the average aromatic hydrocarbon molecule of sour crude, naphthenic rings with long side chains predominate.

In agreement with the concepts concerning the structure of hydrocarbons with a high viscosity index, it is the properties indicated of the aromatic hydrocarbons, separated from sour crude, which provide the advantages of these oils in comparison with oils obtained from another raw material.

The Influence of the Group-Structural and Chemical Composition of Petroleum Oils on Their Operating Properties

There is a specific relationship between the group-structural and chemical composition of TRD petroleum oils, on the one hand, and their operating properties, on the other. First of all this pertains to the viscosity-temperature properties, the thermal oxidation stability and the corrosive activity of the oils.

The content of significant quantities of aromatic hydrocarbons in oil from Tróitsko-Anastas'yevka crude, mainly dicyclic with short side chains, causes a steep viscosity-temperature curve and poor low-temperature oil properties; according to these indicators this oil is inferior to oils from other crudes. During the removal of part of the aromatic hydrocarbons by means of deep cleaning with sulfuric acid, the low-temperature and viscosity characteristics of oils are noticeably improved, but their thermal oxidation stability simultaneously deteriorates (see Table 51, specimens 1 and 2 of MK-8 oil).

Oils from sour crudes such as MS-6 and transformer oils contain relatively few aromatic hydrocarbons (18-21%), while aromatic hydrocarbons desorbed by isocctane contain few rings; naphthenic rings with long paraffin chains predominate in the aromatic hydrocarbons desorbed by benzene. Aromatic hydrocarbons of this type have a high viscosity index, in connection with which oils from sour Tuymazy crude are distinguished by good viscosity-temperature properties. This must be taken into consideration during the choice of a raw material for the manufacture of oils, if their low-temperature characteristics are of decisive import.

Oils of diverse origin and depth of cleaning possess different thermal oxidation stabilities (see Tables 29 and 51), which factor is also influenced by their group-structural and chemical composition. Oils prepared from Tuymazy and Zhirnovsk crudes by means of solvent refining are inferior insofar as thermal oxidation stability is concerned to oils prepared from Troitsko-Anastas'yevka and Balakhany crudes by sulfuric acid cleaning. Oils from Tuymazy and Zhirnovsk crudes are more easily oxidized, which is explained by the insufficient content in these oils of natural oxidation inhibitors. The hydrocarbons contained in these oils of naphthene-aromatic structure (not more than 21%) have weak antioxidation properties and during oxidation are themselves capable of producing acid products. Oils prepared from Troitsko-Anastas'yevka and Balakhany crudes are more oxidation-resistant, since they contain a sufficient quantity of natural oxidation inhibitors, mainly consisting of heavy condensed aromatic hydrocarbons with short side chains. A study of the influence of adding to MK-8 oil, prepared from Balakhany crude (GOST 6457-66), various aromatic hydrocarbons separated from the same oil revealed that the best antioxidation properties are possessed by heavy aromatic hydrocarbons with a refractive index of 1.6051 and a specific dispersion of 257. These hydrocarbons were obtained by their desorption from silica gel with benzene. The foregoing confirms that the specified aromatic hydrocarbons are sufficiently active oxidation inhibitors.

It is characteristic that if type MK-8 oil is obtained from Troitsko-Anastas'yevka crude by means of distillate cleaning, during which the aromatic hydrocarbons of the oil are not touched at all (see Chapter Three), then such oils have improved oxidation stability. And, on the other hand, in all cases when the content of heavy aromatic hydrocarbons is reduced, the thermal oxidation stability of petroleum oils falls. Thus the thermal oxidation stability of MK-6 oil of narrow fractional composition prepared from Troitsko-Anastas'yevka crude is, in practice, on the borderline of GOST requirements (residue 0.1% and acidity 0.35 mg KOH/g) , since a part of the heavy aromatic hydrocarbons remains in the tail fractions of the distillate, which does not enter into the composition of MK-6 oil. The stability of MK-8 experimental oil, prepared from Troitsko-Anastas'yevka crude, after deep cleaning by sulfuric acid also falls (see Table 51),

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although the content in the oil of aromatic hydrocarbons remains relatively high (26.1%). This is caused first of all by the removal from the oil during sulfuric acid cleaning of condensed aromatic hydrocarbons, which are weakly shielded by paraffin chains or naphthenic rings. Thus the acid number of MK-8 oil (specimen 2), obtained by means of distillate cleaning by 50% sulfuric acid, amounts to 1.2 mg/g, while the acid number for MK-8 oil (specimen 1), obtained by cleaning with the usual 6% sulfuric acid, does not exceed 0.2 mg/g. The introduction of quite insignificant quantities of Ionol into deeply cleaned oils causes their oxidation stability to increase sharply. Thus in adding 0.5% Ionol to MK-8 oil (specimen 2), prepared from Troitsko-Anastas'yevka crude, the acid number after oxidation is reduced from 1.2 to 0.02 mg KOH/g. Simultaneously lead plate corrosion (determined in 2 hr on the PZZ device) is reduced from 224 to 3 g/m^2, which emphasizes the close relationship between the corrosive properties of petroleum oils and their thermal oxidation stability.

Due to the insufficient content of natural oxidation inhibitors in the MS-6 oil, prepared from Tuymazy sour crude, 0.2% Ionol was introduced into the oil during preparation. This increased the thermal oxidation stability to the required standards, since MS-6 has a high Ionol susceptibility. MK-6 oil, prepared from Troitsko-Anastas'yevka crude, and containing up to 36% of aromatic hydrocarbons displays the lowest Ionol susceptibility.

The thermal oxidation stabilities of various batches of MK-8 oil prepared from Balakhany crude and from a mixture of Baku crudes are not identical. They differ among themselves and in their Ionol susceptibility (see Chapter Three). This is caused by variations in the composition of the initial crudes.

A Change in the Chemical Group Composition During Extended TRD Operation

The chemical group composition of petroleum oils, as a rule, does not undergo intensive changes during extended operation in TRD's. Thus the chemical group composition of MK-8 and MS-6 oils after 100 and 300 hr of engine operation shows insignificant changes (Table 54). The composition of MK-6 oil shows a more noticeable change, consisting mainly of an increase in resin content in the oil (apparently as a result of heavy aromatic hydrocarbons) and a fall in the methane-naphthenic hydrocarbon content.

Table 54. A Change in the Chemical Group Composition of Petroleum Oils
During TRD Operation (in %)

Oil	Duration of oil operation hr	Methane-naphthenic hydrocarbons	Aromatic hydrocarbons			Resins	Solid oxidation products
			Light	Medium	Heavy		
MK-8 from Balakhany crude	-	75.3	8.1	8.1	7.0	0.9	-
"	10?	76.5	7.5	7.5	6.8	1.6	-
MK-6 from Troitsko-Anastas'yevka crude	-	62.5	8.8	17.2	9.8	0.9	-
"	100	62.5	8.0	16.8	8.8	3.1	-
""	300	60.0	10.9	17.3	8.0	2.9	-
MS-6 from Tuymazy crude	-	81.4	12 1	2.3	3.5	0.4	-
"	100	82.0	9.4	2.4	4.2	0.9	-
"	300	81.0	9.9	2.5	3.9	1.4	-
MK-8 from Troitsko-Anastas'yevka crude (deep cleaning)	-	72.6	10.2	11.3	4.6	0.4	-
"	100	62.4	10.4	11.0	7.4	7.0	1.6
"	300	65.3	9.9	13.8	6.5	4.1	-

* Cleaned with 50 % sulfuric acid

Deeply cleaned MK-8 oil, prepared from Troitsko-Anastas'yevka crude, shows the most change in chemical group composition; the quantity of methane-naphthenic hydrocarbons is reduced by 8-10% with a certain increase in the quantity of heavy hydrocarbon and a significant increase in the resin content. After 100 hr of operation in an engine which was thermally stressed to a greater extent than the engine in which the oil operated for 300 hr, solid products of intensive oxidation were detected.

It is apparent that in oils with a low content of natural antioxidants, the methane-naphthenic hydrocarbons oxidize; in oils with good antioxidation properties it is basically the content of aromatic hydrocarbons, from which resins are apparently formed, which undergo changes.

Investigations of MK-6 oil prepared from Tıoitsko-Anastas'yevka crude, conducted by I. G. Shmelev, have revealed that the group structural composition of petroleum oils during extended TRD operation remain practically constant (Table 55).

Table 55. A Change in the Group-Structural Composition of MK-6 Oil During Extended TRD Operation

Duration of operation of oil in engine hr	Group structural composition				
	Hydrocarbon content, %		Average No. of rings in hydrocarbon molecule		
	Aromatic rings	Naphthenic rings	Paraffin chains	Aromatic	Naphthenic
fresh oil	21.0	32.7	46.3	0.69	1.34
100	20.8	38.0	41.2	0.62	1.48
200	21.4	36.4	41.4	0.62	1.99
300	22.4	36.2	41.4	0.62	1.80

* The group-structural composition was calculated by the n-d-M method.

CHAPTER TWELVE

LUBRICANTS FOR TURBOPROP ENGINES

Petroleum and synthetic oils are employed for the lubrication of TVD's.

The presence in TVD's of reducers makes it necessary to employ oils with an increased lubricating capacity; therefore in these engines oils with a higher viscosity are used (4-13 cs at 100°C or approximately 15-70 cs at 50°C) than in the TRD (2.5-3 cs at 100°C).

The designs of domestic TVD's differ radically, therefore the operating conditions for their lubricants are also not identical (Table 56); there are therefore different requirements for lubricants.

In the more powerful TVD's, the number of revolutions of the turbine shaft is less, however the contact stress on the gear teeth is higher and the oil flow in the engine in connection with increased oil heat removal is greater than in low-power engines. The oil temperature at the input and at the output of engines of both types is approximately identical.

Due to the high load on the reducer gear teeth in high-power engines, oils are employed with an initial viscosity of 10-13 cs at 100°C, whereas oil viscosity, employed in low-viscosity engines, is 4-6 cs.

The starting temperature of various domestic engines without preheating at low temperatures is approximately -5 and -25°C, which is governed by the viscosity of the oils employed in these engines and by the power of their starter assemblies.

Types of Oils

Petroleum Oils

Low-viscosity petroleum oils of the transformer or MK-8 type have insufficient lubricating properties and may not be employed in TVD's. In piston engine aviation for a number of years low-viscosity residual oils of the MK-22 type have been successfully employed; these are distinguished by

good lubricating properties but their low-temperature properties do not comply with TVD requirements. Therefore a blend of low-viscosity and high-viscosity petroleum oils, in addition to special synthetic lubricants, are employed in domestic TVD's.

Table 56. Operating Conditions for Lubricants in Domestic TVD's

Engine and load operating conditions	Engine power, hp	
	4,000	Above 7,000
velocity of turbocompressor shaft rotation under all conditions, rpm	12300 ± 90	8300 ± 50
maximum stress (according to Hertz) on gear reducer teeth, kg/mm^2	95 – 100	114 – 124
oil temperature, °C		
at engine input		
recommended	70 – 80	70 – 80
minimum permissible	40	40
maximum permissible	90	85
at engine output (maximum permissible)	115	Not above 115
oil pressure in engine oil system, kg/m^2	3 – 4.5	4
pumped oil flow under normal conditions at recommended oil temperature at input, kg/min	100 – 135	170 ± 15
average oil consumption, kg/hr	No more than 1.5	No more than 2.8
heat absorbed by oil under normal conditions at recommended oil temperature at input, kcal/min	No more than 850	No more than 1850
minimum engine starting temperature without preheating, °C	–25	–5

For the lubrication of type AI-20 engines a so-called low-viscosity oil blend consisting of 25% MS-20 oil (or MK-22) and 75% MK-8 oil (or transformer oil) is employed; and for high-power engines, a high-viscosity blend is employed, containing 75% of the high-viscosity oils indicated and 25% of low-viscosity oils.

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The differenc₁ in oil composition determines their operating proper-
ties.

The specifications for petroleum lubricants for TVD's and their
fundamental quality indicators according to analytical data are shown in
Table 57.

Table 57. Specifications for Blends of Petroleum Lubricants for TVD's and
Average Quality Indicators

Indicators	Low viscosity mixture			High-viscosity mixture	
	Specifi-cations	Test results		Specifi-cations	Test results 75% MS-20 oil + 25% trans former oil
		75% transformer oil (MK-8) + 25% MK-22	75% transformer oil (MK-8) + 25% MS-20		
density o_4^{20}	0.8-0.9	0.88-0.89	0.88-0.89	0.8-0.9	-
kinematic viscosity cs					
at 100°C	4-6	4.40-4.60	4.15-4.25	10-13	9.5-11.0
at 50°C	15-20	16.60-16.98	15.16-15.69	55-71	-
at 20°C	-	1636-1685	1600-1615	-	50000 (at-25°C)
Temperature flash point in open vessel, maximum......	138	160	155	150	140-164
pour point,maximum ..	-40	-41 -42	-45 -46	-20	-20 -22
acid No. mg KOH/g max	0.05	0.01	0.01	0.1	0.05-0.09
ash content, % max ..	0.005	Traces		0.005	0.005
cokability, % max....	0.15	0.16-0.17	0.08-0.09	0.03	0.03
content water		Not available			
water-soluable acids and alkalis		"			
mechanical impurities		"			

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In connection with the difference (authorized by standards) in the properties of commercial oils used for blends, the quality of the blends fluctuates considerably, which must be taken into consideration.

The use of oils of narrow fractional composition such as MK-6 and MS-6 with improved low-temperature characteristics permits the preparation of oil blends with good starting properties, not inferior to the ordinary oil blends with respect to other operating properties (Tables 58 and 59).

Table 58. Physicochemical Properties of Low-Viscosity Blends Prepared from Oils of Narrow Fractional Composition

Indicators	35% MK-22				35% MS-20			
	65% MK-6		65% MS-6		65% MK-6		65% MS-6	
	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
Density ρ_4^{20}	0.882	0.865	0.869	0.866	0.896	0.893	0.865	0.865
Kinematic viscosity, cs								
At 100°C	4.2	4.1	4.4	4.6	4.0	4.4	4.2	4.4
At 50°C	14.7	14.4	15.0	16.8	14.4	15.6	14.6	15.5
Temperature, $^{\circ}$C.								
flash point in open vessel	171	159*	170	160*	156	150*	170	165*
pour point.........	-37	-36	-33	-35	-42	-40	-39	-42
self ignition	-	-	-	-	-	360	-	395
Acid No. mg KOH/g	0.03	none	0.03	none	0.02	0.01	0.05	0.01
Ash content, %	0.005	none	none	none	0.002	none	0.005	none
Cokability, %	0.13	0.16	0.21	0.22	0.06	0.09	0.06	0.05
Stability by VTI method.								
quantity of deposits %	-	-	-	-	-	0.14	-	0.01
acid No. mg KOH/g	-	-	-	-	-	0.40	-	0.16

* Flash point was determined in a closed vessel.

Table 59. Physicochemical Properties of High-Viscosity Blends Prepared from
Oils of Narrow Fractional Composition

Indicators	65% MK-22		70% MK-22 + 30% MS-6	65% MS-20		70% MS-20	
	35% MK-6	35% MS-6		35% MK-6	35% MS-6	30% MK-6	30% MS-6
Density o_4^{20}	0.891	0.886	0.885	–	0.878	0.894	0.881
Kinematic viscosity, cs							
At 100°C	9.1	9.3	9.5	8.5	8.8	9.3	9.3
At 50°C	47.2	47.4	54.5	43.3	41.6	49.2	49.6
Temperature, °C							
flash point in an open vessel.	179	187	173	166	185	158	172
pour point	-23	-21	–	-30	-29	–	–
self ignition	–	–	–	–	–	415	390
Acid No. mg KOH/g	0.02	0.02	none	0.02	0.05	none	none
Ash content, % ..	0.005	0.002	none	0.005	0.005	none	none
cokability, %....	0.55	0.50	0.44	0.29	0.28	0.25	0.18

Petroleum oils for TVD's are prepared by blending distillates and residual oils (in the required volumetric ratios) at the aircraft operating locations. In order to prepare oil blends, reservoirs or tanks are used which have mixing facilities (oil fillers, oil and water heaters, devices for oil regeneration or special mixers). After the oil is poured into a container, it is agitated for 20-30 min at 20-25°C and the correctness of blend composition is checked according to the viscosity at 100°C, which must correspond to the requirements established by the specifications for a given oil blend.

The use in domestic TVD's of two blends which -differ in quality is not advantageous. In this connection storage is more complex, the technical servicing of aircraft is made more difficult, and duplicate facilities are required. When improperly prepared blends are made at the points of consumption, their quality frequently does not agree with established requirements. Therefore it is advantageous to employ lubricants of the same type, prepared at oil refineries, for the lubrication of all domestic TVD's.

An Investigation of Oil Quality

In the specifications for TVD oil blends, in contrast to the specifications for TRD oils, the viscosity at low temperatures and also the thermal oxidation stability are not regulated. Nevertheless these indicators are of particular importance in oil usage in TVD's.

The temperature operating conditions of lubricants in domestic TVD's (85-90°C at the input and 115-120°C at the engine output) cause a certain amount of oxidation of petroleum oils, but this circumstance does not limit the possibility of their application. However, in the future in connection with the development of TVD designs and the development of improved oils for these, serious attention must be devoted to the thermal oxidation stability of these oils; it will also be necessary to consider more stringent requirements for their low-temperature properties.

The quality of petroleum oils for TVD's is evaluated using fundamentally the same laboratory methods that are used for TRD oils. However, in connection with TVD oil characteristics, several methods were changed. Among these methods are the determination of thermal oxidation stability of oils (determined in the VTI device at 50°C for 50 hr), the flash point (an open vessel), etc.

Viscosity and Low-Temperature Properties

One important problem is the improvement of starting conditions for domestic TVD's at low temperatures. While not considering here methods involving design changes, we shall note that starting at low temperatures may be facilitated by dilution of the lubricant with fuel, by preheating of the oil or the engine with special airdrome preheating devices, and also by the employment of oils with improved low-temperature characteristics.

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The use of lubricants with good starting properties is most advantageous. Such properties are to a large extent possessed by oil blends obtained by using MS-20 oil; these blends have a flatter viscosity-temperature curve than blends containing MK-22 oil (Table 60).

Table 60. The Viscosity-Temperature Characteristics of TVD Oil Blends

Blend composition	Kinematic viscosity, cs, at temperature, °C					
	100	50	20	0	-30	-40
High-viscosity blends						
75% MS-20 + 25% MK-8	11.3	68.1	383	2320	15.10^4	-
75% MK-22 + 25% MK-8	12.3	75.4	425	3357	18.10^4	-
75% MS-20 + 25% transformer oil	10.5	63.0	396	2400	3.10^5	-
Low-viscosity oils						
75% transformer oil + 25% MS-20	4.2	16.0	62.9	243	6117	-
75% transformer oil + 25% MK-22	4.4	16.1	63.6	259	11195	-
75% MK-8 + 25% MS-20	4.4	17.8	66.1	281	5923	21500
75% MK-8 + 25% MK-22	4.4	16.7	64.3	247	10590	36000

This circumstance must be considered during the operation of aircraft with TVD's in regions of steady low temperatures. With the same high-viscosity base, blends containing MK-8 oil have better low-temperature properties than those containing transformer oil (see Table 60). With respect to the remaining physicochemical indicators, such as viscosity at positive temperatures, acid number, ash content, etc., these blends show no essential differences.

The viscosity of lubricants which provide for reliable engine starting with electrical starters, for the majority of foreign and domestic engines, falls within the limits of 3600-4600 cs. Such viscosities for a low-viscosity blend is achieved at a temperature of approximately -25°C, and for a high-viscosity blend, at -5°C. These temperatures are also considered to be the limit of TVD starting during the utilization of oil blends without preheating, although sometimes in the case of high-viscosity blends the engine is successfully started at -10°C.

At higher temperatures the engine is supplied with hot oil or is heated with hot air (100-120°C), which is delivered from special airdrome preheating devices of the MP-85 type.

Table 61. The Viscosity-Temperature Characteristics of Blends of Standard Oils and Those Obtained from Oils of Narrow Fractional Composition*

Blend Composition	Kinematic viscosity, cs, at temperature, °C							
	100	50	20	0	-10	-20	-30	-40
	Low-viscosity blends							
25% MS-20 + 75% MK-8	4.4	16.0	62.4	233	—	1734	7210	21.10^3
25% MS-22 + 75% MK-8	4.4	16.7	64.3	247	—	1794	7840	36.10^3
25% MS-20 + 75% transformer oil	4.5	17.1	67.6	272	688	1952	8026	26.10^3
35% MS-20 + 65% MS-6	4.3	15.5	54.6	198	430*	1328	5150	$13.5.10^3$
35% MS-20 + 65% MK-6	4.4	15.6	62.7	248	590*	1676	5973	16.10^3
35% MS-22 + 65% MS-6	4.6	16.2	—	221	450*	1566	4200*	$17.6.10^3$
35% MK-22 + 65% MK-6	4.6	17.1	64.3	222*	525*	1932	4700*	$18.5.10^3$
	High-viscosity blend							
75% MS-20 + 25% MK-8	11.3	68.1	383	2320	6986	25.10^3	—	—
75% MK-22 + 25% MK-8	12.3	75.4	425	3357	7070	27.10^3	—	—
75% MS-20 + 25% transformer oil	10.5	63.0	390	2400	7800	32.10^3	—	—
70% MS-20 + 30% MS-6	9.5	49.6	254	1100	4000*	13.10^3	—	—
70% MS-20 + 30% MK-6	9.5	48.9	257	1266	3800*	19.10^3	—	—
70% MK-22 + 30% MS-6	9.6	52.1	270	1406*	3700*	17.10^3	—	—
70% MK-22 + 30% MK-6	9.5	57.2	302	1640*	3800*	18.10^3	—	—

* The viscosities of low-viscosity blends are at -40°C, and high-viscosity blends at -20°C, as well as the viscosities marked by asterisk, calculated according to the monograms of I. G. Semenov.

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Therefore the fundamental shortcoming of oil blends in use is reflected in their unsatisfactory starting characteristics. Therefore the most promising oil blends, prepared from low-viscosity components of narrow fractional composition are MK-6 and MS-6 oils. The significant advantages of these oil blends from the point of view of their low-temperature proper-ties may be seen in Table 61 (the other physicochemical characteristics were shown in Tables 58 and 59).

The best among high-viscosity blends is the blend consisting of 70% MS-20 and 30% MS-6, having a viscosity at -20°C of 13,000 cs, while the viscosity of a corresponding standard blend consisting of 75% MS-20 and 25% MK-8 is 25,000 cs. The viscosity of both oil blends at 100°C complies with specification standards and the anti-wear properties are similar in accordance with an evaluation made on a four-ball friction machine.

Among low-viscosity oil blends, a blend consisting of 35% MS-20 and 65% MS-6 with a viscosity at -40°C of 14,000 cs is of great interest. The viscosity at -40°C of a corresponding standard blend is 21,000 cs.

In employing oil blends obtained by using oils of narrow fractional composition, the reliable starting temperature (without preheating) of domestic TVD's is reduced: for AI-20 type engines the reduction is to -30°C (with a standard blend, from -23 to -25°C), and for high-power engines, from -15 to -17°C. Viscosity-temperature curves which permit evaluating and selecting the required viscosity level for TVD oil blends at specified temperatures are shown in Figure 35.

VNII NP-7 and VNII NP-4u-2 synthetic oils, authorized for use in TVD's, have better low-temperature characteristics than petroleum oil blends.

In addition to unsatisfactory starting properties, a shortcoming of standard oil blends is their quality deterioration in extended TVD oper-ation.

A typical qualitative change in an oil blend within an operating engine is an increase in oil viscosity as a result of vaporization of light frac-tions of distillate components. Laboratory investigations reveal that the vaporizability of a blend of 75% transformer oil and 25% MS-20 (after vapor-ization of 100 g oil in 5 hr at 145°C, with air delivery of 1.5 l/hr and a

residual pressure of 198 mm Hg) is almost twice as high as the vaporiz-
ability of a blend in which the component ratio is reversed (Figure 36).
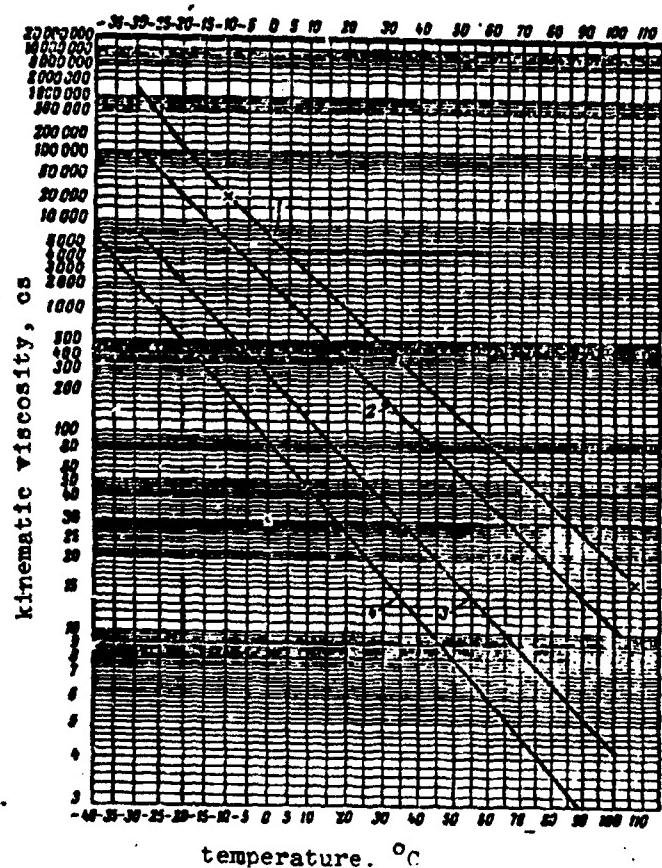
Figure 35. The viscosity of oil blends for TVD's as a function
of temperature: 1, MS-20 oil; 2, 75% MS-20 + 25% transformer
oil; 3, 25% MS-20 + 75% transformer oil; 4, Transformer oil

During operation in an AI-20 engine under bench-test conditions,
the viscosity of a low-viscosity blend (75% transformer oil and 25% MS-20
oil) during 100 hr of operation increased on the average from 4.5 to
4.9-5 cs.

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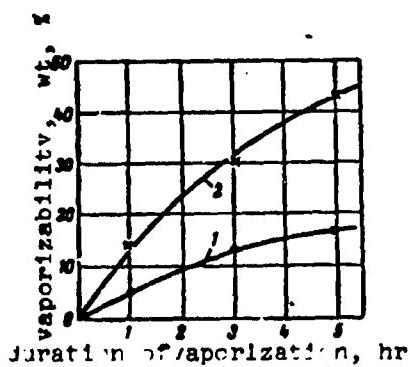
Figure 36. The vaporizability of oil blends under laboratory
conditions: 1, 75% MS-20 + 25% transformer oil: 2, 25%
MS-20 + 75% transformer oil
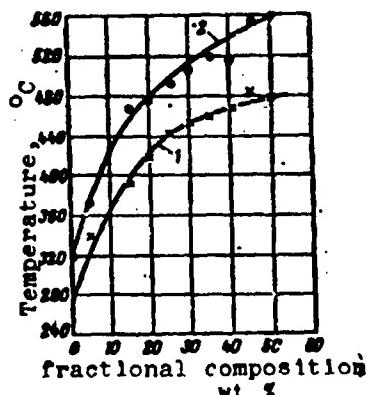
Figure 37. A change in the fractional composition of oil blends
during operation under bench-test conditions: 1, 75% MS-20 +
+ 25% transformer oil, fresh blend; 2, 75% MS-20 + 25% transformer
oil after operation in a TVD

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Under summer conditions the viscosity of oil blends increases more intensively than during bench-test conditions, as a result of high vaporizability of the oil while the aircraft is gaining altitude. Data ××××××× concerning the change in viscosity, pour point and other physicochemical indicators for a low-viscosity blend (75% MK-8 and 25% MS-20) during operation in the AI-20 engine during summer conditions are shown in Table 62.

Table 62. A Change in the Basic Physicochemical Properties of a Low-
Viscosity Oil Blend (25% MS-20 + 75% MK-8) During Operation in the
AI-20 Engine Installed in the IL-18 Aircraft

Indicators	Duration of oil operation, hr			
	0	50	100	200
Density ρ_4^{20}	0.888	0.885	0.887	0.887
Kinematic viscosity, cs ..... At temparature°C				
100	4.4	5.2	5.8	6.1
50	16.4	21.1	24.6	26.3
0	262	386	520	608
-10	619	982	1344	1741
-20	1940	3540	4815	6020
-25	3850	7950	10260	13770*
Temperature,°C				
flash point in open vessel	160	167	169	174
pour point	-35	-35	-31	-28
Acid No. mg KOH/g	0.060	0.065	0.046	0.090
Cokability, %	0.10	0.122	0.143	.218
Mechanical impurity content %	none	o.o3	0.10	0.05

* In a number of cases the viscosity of low-viscosity blends after 150-
200 hr of operation in the AI-20 engine increases under summer cond-
itions at -25°C from 20,000 to 23,000 cs.

The properties of a high-viscosity blend (75% MS-20 and 25% transformer oil) show similar changes during extended operation in a TVD (Figure 37 and Table 63).

Thermal Oxidation Stability

The thermal oxidation stability for TVD oils is not regulated by specification requirements; nevertheless this indicator has a great deal of significance for the evaluation of oil efficiency within an engine.
Table 64 shows data concerning the thermal oxidation stability of various and their components obtained after oxidation according to GOST 981-56 for

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for 50 hr at 120°C with the application of air to the test tube for oxidation purposes.

Table 63. Change in the Physicochemical Properties of a High-Viscosity Oil Blend (75% MS-20 and 25% Transformer Oil) During Operation in an Engine Under Bench-Test Conditions

Engine No.	Duration of oil operation hr	Kinematic viscosity, cs at temperature °C			Acid No. mg KOH/g	Coka-bil-ity %
		100	50	-35*		
1	initial oil blend	10.5	60.4	34.10^4	0.0^r	0.19
	40	11.8	69.2	37.10^4	0.08	0.27
	80	12.6	69.3	–	0.1?	0.27
	15?	12.8	71.6	42.10^4	0.10	0.26
2	initial oil blend	10.1	52.7	115.10^3	0.05	0.12
	4?	10.8	56.5	15.10^4	0.06	0.15
	1??	12.5	60.8	18.10^4	0.07	0.16
	160	12.7	61.6	–	0.07	0.20
	200	12.8	63.0	18.10^4	0.09	0.12
3	initial oil blend	10.6	52.5	–	0.04	0.20
	80	11.5	55.7	$15.5 .10^4$	0.04	0.16
	120	11.8	63.4	18.10^4	0.12	0.22
	180	12.0	69.7	32.10^r	0.13	0.25
	200	12.9	68.6	$3.10^?$	0.18	0.22

* Calculated in Accordance with a nomgram (GOST 2878-48).

After oxidation in all oils tested, deposits did not exceed 0.15-0.16%, and the acid number was 0.42-0.48 mg KOH/g. Apparently these oils, obtained by using MK-6 and MS-6 oils are comparable insofar as stability is concerned to standard oil blends.

Recently thermal oxidation stability of petroleum and synthetic oils for TVD's have been determined by a stringent method, the conditions of which are similar to oil operational conditions in engines. According to this method, a quantity of oil consisting of 30 g is oxidized in a VTI device for 50 hr at 150°C in the presence of copper and iron spherical catalysts with an air delivery at the rate of 3 l/hr to each test tube for

oxidation. Under these conditions deposits after oxidation consisted on the average of not more than 0.32-0.35%, and the acid number was not more than 0.12-0.15 mg KOH/g.

Table 64. The Thermal Oxidation Stability of Petroleum Oils and Their Blends (GOST 981-56)

Blend Composition	Indicators after oxidation	
	Quantity of Deposits, %	Acid No. mg KOH/g
75% MS-20 + 25% MK-8	0.15	0.37
25% MS-20 + 75% MK-8	0.12	0.34
70% MS-20 + 30% MS-6	0.05	0.32
70% MS-20 + 30% MK-6	0.03	0.35
70% MK-22 + 30% MS-6	0.04	0.25
35% MS-20 + 65% MS-6	0.01	0.18
35% MS-20 + 65% MK-6	0.16	0.48
35% MK-22 + 65% MS-6	0.03	0.20
30% MK-22 + 70% MS-6	0.06	0.42
20% MK-22 + 80% MS-6	0.07	0.35
MK-8	0.10	0.35
MS-6	0.01	0.02
MK-6	0.07	0.31

The lubricant in a TVD is oxidized mainly in a thin layer on hot engine parts; however in the Soviet Union thermal oxidation stability of oils is evaluated by means of the thin layer oxidation method only during research work. Nevertheless the method of determining the thermal oxidation stability of TVD oils in a thin layer on a hot panel (see Chapter Six) reveals the clear dependence of the quantity of deposits on temperature and permits comparing the oxidizability of various TVD oil blends. For all oils tested the quantity of panel deposits at 180°C fell within the range of 0.0011-0.0046 g, and at 260°C these values converged and amounted to 0.0839-0.102 g.

Anti-wear Properties

The anti-wear properties of TVD oils are determined under laboratory conditions on a four-ball friction machine at the usual temperatures in accordance with the one-minute technique.

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Typical indicators for the anti-wear properties of standard petroleum oil blends and their components are shown in Table 65.

Table 65. The Anti-wear Properties of Oil Blends and Their Components

Blends and Components	Critical film break down load P_k kg	Diameter D_k of wear trace at P_k, mm	Diameter of wear trace, mm at loads, kg					
			15	25	35	45	55	65
75% MK-22 + 25% MK-8	55	0.38	–	0.32	0.33	0.36	0.38	–
25% MS-20 + 75% MK-8	40	0.47	0.26	0.28	0.33	1.05	–	–
MK-22	60	0.44	0.28	0.32	0.36	–	0.41	3.02
MS-20	50	0.26	–	0.36	0.40	0.43	1.24	–
MS-6	30	0.37	0.30	0.35	0.56	–	–	–
MK-8	29	0.48	0.30	0.34	0.50			
Synthetic (VNII NP 4u-2)	70	0.42	–	0.39	0.35	0.37	0.44	1.25

In accordance with the value of the critical oil film breakdown load (P_k) oil blends are approximately equal to or are somewhat inferior to the residual oils MS-20 and MK-22 and surpass low-viscosity distillate oils MK-8, transformer oils, etc. In comparing the P_k indicators of oil blends and their components, it is apparent that the lubricating capability of petroleum oil blends is an additive property.

The lubricating property of TVD oils may be evaluated on a special hearing stand by the number of shaft overrun rpm without a load and with a load (200 kg) and by the ratio of the shaft overrun rpm without a load to the number of shaft overrun rpm with a load. By this method the number of shaft overrun rpm during the utilization of oil blends falls within the range 29,000-36,000, and the ratio of the number of rpm without a load and with a load varies from 3.3 to 3.9.

In lubricating property all of the oil blends tested are similar, which corresponds to the results of the evaluation of the anti-wear properties of these oils on a four-ball friction machine.

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With the aim of bringing the conditions of the evaluation method for anti-wear properties of TVD oil closer to operating conditions in reducers, special closed-circuit heavily loaded gear stands were developed in the USSR (for example, the Sh-3 stand) in which the oil is tested under high load and temperature conditions. The anti-wear properties of oils are evaluated by the condition of the operating surface of the gear teeth and by a change in the qualities of the oil (see Chapter Seven).

The complex of methods of investigating oils containing thickeners, high molecular weight additives and also synthetic oils usually includes evaluation of viscosity change as a result of mechanical destruction, an indicator of thermal destruction, etc.

In connection with quality deterioration of oil blends during their extended operation in TVD's, limits are established for the change in physicochemical indicators of oil blends (technical standards), at which the further use of these oils in engines is authorized, and also quality indicators for the recovery of oil blends (Table 66).

The materials presented above releav that the basic shortcomings of domestic petroleum oils for TVD's are their unsatisfactory starting (low-temperature) properties, and a tendency toward vaporization and oxidation. To a certain extent these shortcomings are not present in domestic synthetic oils for TVD's, and also in oils prepared by the addition of synthetic components and additives to the basic crude.

Blends of domestic petroleum oils utilized for TVD lubrication may be replaced by blends corresponding in viscosity to American or English petroleum oils. Insofar as viscosity and other properties are concerned, the following oils are similar:

Oils	High viscosity	Low viscosity
domestic	Ms-20 or MK-22	transformer or MK-8
foreign	DERD-2472, type B/C (England) and MIL-L-6028B, type 1100 (USA)	DERD-2490 (England) and MIL-O-6081B, type 1010 (USA)

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Table 66. Technical Standards for Used and Reclaimed Oil Blends for TVD's

Indicators	Technical Standards	
	Used Blend	Reclaimed Blend
Density ρ_4^{20}, maximum	0.900	0.900
Kinematic viscosity, cs		
at $100^\circ C$, max	16	16
" $50^\circ C$	52 - 80	52 - 80
Temperature, $^\circ C$		
flash point in open vessel, min	150	150
pour point, max	-20	-20
Acid number, mg KOH/g max	0.25	0.20
Ash content, % max	0.015	0.015
Cokability, % max	0.55	0.55
Water	none	none
Water soluble acids and alkalis	none	none
Mechanical impurities	traces*	none

* Visible mechanical impurities are assumed, except for metallic shavings and sand, in quantity up to five pieces on a watch glass 100 mm in diameter. The quantity of mechanical impurities determined by the weight method is authorized to not more than 0.015%.

Synthetic Oils

One of the fundamental requirements in the development of domestic synthetic TVD oils includes the fact that insofar as possible the same oil must be employed in all types of engines. In this connection synthetic oils VNII NP-4u-2[1] (GOST 10817-64) and VNII NP-7 (GOST 12246-66) have been developed in the USSR.

The VNII NP-4u-2 oil is prepared on a crude base, into which synthetic components and a complex of various additives have been introduced. Synthetic lubricants significantly surpass petroleum oils in all basic quality indicators, including low-temperature, anti-wear, lubricating and other properties (Table 67).

Table 67. Basic Properties of Synthetic Domestic TVD Oils

Indicators	VNII NP-4u-2 oil		VNII NP-7 oil	
	GOST 10817-64	factual data	GOST 12246-66	factual data
Kinematic viscosity, cs				
at 100°C	min 9.0	9.0-9.6	7.5-9.0	7.6-7.8
at -35°C	max 4500	4100-4300	max 7500	5390-7050
at -40°C	-	6860-8040	-	12500
Kinematic viscosity at 100° C after stability determin- in a ordance with GOST 10407-63, cs	min 6.6	6.5-6.7	min 7.3	6.4-7.1
Temperature, °C				
pour point	max -56	-57;-60	max; -60	-60
flash point in open vessel	min 135	135-140	min 210	222-224
Acid no. mg KOH/g	max 0.1	0.05-0.06	max 0.3	0.17-0.19
Stability after air oxida- tion at 150°C for 50 hr				
quantity of deposits, %	max 0.1	0.01-0.08	max 0.06	0.025
acid no mg KOH/g	max 0.2	0.04-0.12	max 0.5	0.24-0.46
Antiwear properties on four- ball friction machine				
critical oil film break- down load P_k, kg	min 90	90-95	-	-
P_k ratio of oil to P_k, of MS-20 oil	-	-	min 1.3	1.3-1.5
Plate corrosion test at 150° C, g/m²				
of ShKh-15 steel and of AL-4 aluminum alloy	none	-	none	-
of brass	5	-	1	-

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VNII NP-4u-2 oil has the best low-temperature properties, which permits engine starting without preheating down to temperatures of the order of -25 to -40°C.

The high quality of synthetic oils provides for extended operating capability in TVD's without changing to fresh oil. Notwithstanding the fact that synthetic oils are more expensive than petroleum oils, the effectiveness of their employment causes no doubts. Thus according to calculated data the use of synthetic oil, which requires no engine preheating at temperatures down to -35 -- -40°C, permits saving up to 300 rubles per year for each IL-18 aircraft with four TVD's. The higher cost of synthetic oil is balanced by an increase in engine life during the employment of this oil as a result of reduced wear.

We must note the corrosiveness of several synthetic oils (for example, VNII NP-7) th respect to rubber; in this connection the employment of special oil-resistant aviation rubber is required. These oils also have a specific toxicity, therefore contacts with the skin or ingestion into the body must be avoided.

The quality of synthetic oils during TVD operation shows no significant change. Some oils show a reduction in viscosity as a result of the mechanical destruction of viscosity additives contained in the oils. Thus the VNII NP-4u-2 oil in the process of operation in the AI-20 engine for 100 hr shows a viscosity decrease at 100°C from 9 to 6 cs, i.e. by approximately 28%. However, this reduction is balanced by a certain viscosity increase as a result of oil vaporization.

Foreign Lubricants

Leading firms of the USA and England are actively occupied in the development of new high-quality TVD oils, while paying particular attention to their thermal oxidation stability, load-carrying capacity and starting characteristics. A lubricant for contemporary TVD's must pump through and provide starting of engines at temperatures down to -60°C, and insofar as stability is concerned it must be capable of operation down to temperatures of 200-250°C.

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Table 68. Types and Basic Properties of Synthetic TVD Lubricants in England and in the USA

Indicators	USA Specification					English specification		
	MIL-L-6808 (Turboil-15)					DERD-2487 (Turboil-35**)		
	Type B		Type C					
				Factual data			Factual data	
	Technical requirement	Factual data	Technical requirement	Sample 1	Sample 2	Technical requirement	Sample 1	Sample 2
Kinematic viscosity, cs								
At 100°C, minimum	3	3.1-3	3	3.6	3.3-3.6	7.5	7.4?	7.5-7.9
" 38°C "	11	11.4-14.2	11	14	12.7-14.2	39	33.4	3ᵉ-38
" -54°C maximum	13000	8000-13000	13000	1900*	10000-13000	13000	11590*	10650-12500
Temperature, °C								
pour point, minimum	-60	-60 -68	-60	-60	-60 -68	-50	-54	-52 -54
flash point in an open vessel, min.	177	196-221	221	221	204-232	215	244	230-240
Acid no. mg KOH/g, max	-	-	-,	-	-	0.2	-	0.10-0.17

* The viscosity was determined at -40°C

** Turboil-7..

Both petroleum and synthetic oils are employed for TVD lubrication abroad; however, a tendency is now observed toward the limitation of the use of petroleum oils and their replacement with synthetic oils which satisfy the requirements of contemporary TVD's to a greater extent.

The types and basic quality indicators for foreign TVD oils are shown in Tables 68-70.

Table 69. The Types and Basic Properties of TVD Petroleum Oils in the USA

Indicators	Specification			
	MIL-L-5081B Type 1010	MIL-0-6082A Type 1100	MIL-L-6282B Type 1100	MIL-L-25336* -
	Turboil 2	Aviation oil 1065	Aviation oil 1100	-
Kinematic viscosity, cs				
at +7.8°C minimum............	10.0	-	-	11.0
" ,°C ,°C "	2.5	20.5	19	3.0
maximum	-	-	21	-
at -40°C	2600	-	-	1300
Temperature, °C				
flash point in open vessel	132	252	243	204
pour point	-57	-18	-12	-60
Acid no.,mg KOH/g	0.1	0.1	0.1	-
Viscosity index	-	100	95	-

* This oil has improved load-carrying capacity.

The majority of TVD lubricants are manufactured by firms in the USA and England, they deliver these oils to countries with which they have economic and military ties. Synthetic oil produced by the Shell firm according to the DERD-2487 specification) under the name Turboil-750 is widely employed in civil and military turboprop aviation; sometimes these oils are marketed as type J5H. The oil is employed in civil aviation for such TVD's as Rolls Royce, Avon, Dart, Spey and Tyne, Bristol Siddley, etc.

Table 70. Types and Basic Properties of English TVD Petroleum Oils

Indicators	Specification			
	DERD 2472 Type B	DERD 2479/0	DERD 2479/1	DERD 2490
	Aviation oil 1080	Turboil-9	Turboil-9B	Turboil-3
Density ρ_4^{20}	-	0.870	0.870	0.876
Kinematic viscosity, cs				
at 37.8°C minimum	-	-	-	13.0
at 98.9°C minimum	18.8	5.7	8.7	2.5
maximum	21.2	9.3	9.3	-
at -40°C	-	Solid		7000
Temperature, $^{\circ}$C				
flash point in open vessel	243	210	210	143*
pour point	-12.2	-29	-29	-46
Saponification no. mg KOH/g	0.5	-	1.0	1.0
Acid no., mg KOH/g	0.1	0.3	0.3	0.1
Viscosity index	95	115	115	71
Ash content, %	-	0.01	0.01	0.01

* The flash point was determined in a closed vessel.

The Esso firm, which was one of the first to manufacture Turboil-35 according to the DERD-2487 specification, placed on the market a synthetic oil of a new type -- Turboil-724 Extra, which is distinguished by high thermal oxidation stability. After tests in three "Vanguard" aircraft with three Rolls Royce Tyne engines for approximately 1300 hr, friction points and parts of the engines were in good condition.

Since the starting properties of Turboil-750 synthetic oil are not high enough, Turboil-15 oil has enjoyed widespread application, as well as petroleum oils Turboil-2 and Turboil-3, which have been employed for a long time in turboprop aviation. It should be noted that in the USA several aviation petroleum oils intended for piston-engine aviation (type 1100) are employed for TVD lubrication.

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Anti-wear, antioxidation, depressant and anticorrosion additives are
introduced into foreign TVD oils. Usually these additives are multifunctional
ones. In the USA frequently tricresyl phosphate (up to 5%) is frequently
used as an anti-wear additive, and phenyl-α-phenylamine and phenthiazine
(up to 0.5%) are used as antioxidation additives. Compounds containing
chlorine, phosphorus and sulfur are introduced into oils which operate under
extremely high-pressure conditions.

An attempt is being made abroad to obtain oils suitable for the simul-
taneous lubrication of gear reducers and turbocompressor assembly bearings by
the introduction of highly effective additives into low-viscosity petroleum
oils in order to improve their lubricating properties and their load-carrying
capacity. However, this is not always successful. This may also be said
concerning synthetic TVD oils. For example, the synthetic oil Turboil-35,
with all its positive qualities, frequently does not provide for the lubrica-
tion of highly stressed propeller reducers. Sometimes, therefore, different
oils are employed, which is accomplished by means of different lubrication
systems, in order to lubricate the propeller and the engine, on the one hand,
and the reducer on the other. Turboil-35 is used in the Allison T-56 engine
for reducer lubrication, but the turbocompressor and the propeller are
lubricated with the low-viscosity petroleum oil Turboil-2, type 1010
(specification MIL-O-6081 B).

One of the best reducer lubricants in the USA is the MIL-O-6082A
type 1100 oil. This is a high-viscosity petroleum oil similar in viscosity
to our residual oils MK-22 and MS-20. However, due to high-viscosity, the
delivery of oil into friction points is already impeded at -1°C, and at -15°C
the flow ceases altogether. Therefore, in engines where this oil is employed
for reducers, low-viscosity petroleum oil MIL-O-6081B, type 1010, is employed
to lubricate the turbocompressor.

Petroleum oils of several types are used in England for TVD lubrication.
Oil prepared in accordance with specification DERD-2479/0 of the "Shell" firm
is manufactured with no additive and in accordance with the same specification
(2479/1) with a 1% anti-wear additive, which contains sulfur and phosphorus.
It operates successfully in highly stressed reducers. The low-viscosity
petroleum oil DERD-2490 is also manufactured in two versions: with no

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additive and with 0.1% of stearic acid in order to improve the lubricating properties.

From the data presented in Tables 68-70, it is apparent that English TVD oils are inferior to American oils insofar as low-temperature properties are concerned. This fact is associated with the more moderate climate of England. Oils manufactured in England according to the DERD-2472 specification, type B, and in the USA in accordance with specification MIL-L-6282 B, type 1110, are identical in quality.

Mainly English petroleum oils are used in French turboprop aviation; however, the French petroleum oil Air-3512 is used in many TVD's.

In Canada and in the FRG [Federal Republic of Germany], in addition to English synthetic oil Turboil-35, the American petroleum oil Turboil-2 is also employed for TVD's.

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Footnotes

1. To p. 163. In composition, VNII NP-4u-2 is a semisynthetic oil

CHAPTER THIRTEEN

LUBRICANTS FOR TURBOJET ENGINES ABROAD

Petroleum Oil

In the first TRD's abroad, petroleum lubricants which fully satisfied requirements insofar as lubricating, starting and antioxidation character-istics were concerned were employed. In connection with the modernization of the TRD and the shift in recent years of jet aircraft to supersonic speeds (more than 1100-1200 km/hr), these aircraft employ mainly synthetic lubric-ants. Table 71 shows data concerning the use of various oils in TRD's abroad in relation to the speed of flight of the aircraft.

Petroleum oils are employed abroad mainly for the TRD's of subsonic aircraft, where the oil operating temperature usually does not exceed 115-120°C. Thus in the USA for the engines of aircraft operating at a flight speed of 960-1100 km/hr, petroleum oils are employed which comply with the specification MIL-O-6081B; in England under the same speed conditions oil is employed which complies with the specifications DERD-2479, DERD-2490. etc.

Petroleum lubricants, as a rule, are not employed abroad at the present time for the engines of supersonic aircraft [92-94] due to the increased operating oil temperatures in friction assemblies of the engines up to 250-260°C. Under these conditions the quality of petroleum oils deteriorates significantly (they display insufficient stability, they have increased vaporizability and corrosive activity with respect to metals) and therefore such oils cannot provide engine lubrication for the period of time required.

An exception is the French TRD Atar, installed in the French supersonic fighter d'Assault, in which French and English petroleum oils are employed.

Most of the petroleum oils are produced by firms of the USA and England, which provide these to European countries, as well as to Canada and Australia. In conjunction with this, petroleum oils of local manufacture are also used in France and Canada (for example, Air-3512 in France and 3-GR-38 in Canada).

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Table 71. The Use of Lubricants in the Jet Aviation of Foreign Countries
in Relation to Aircraft Speed of Flight

Country	Flight speed km/hr	Oil	Specification
USA	960	petroleum	MIL-O-6081B
	960	synthetic	MIL-L-7808B
	1100	petroleum	MIL-L-7808B
	1100	synthetic	MIL-O-6081B and later modifications to this specification
	1200	"	
		synthetic	MIL-O-6081B and later modifications to this specification
	1.5*	synthetic	MIL-O-6081B and later modifications to this specification
	2.0*	synthetic	MIL-O-6081B and later modifications to this specification
	2.5*	synthetic	MIL-O-6081B and later modifications to this specification
England	960	petroleum	DERD-2479
	1500	petroleum	DERD-2490
	1100	petroleum	DERD-2479
	1100	synthetic	DERD-2487
	1.0	synthetic	DERD-2497
	2.0	synthetic	DERD-2497
France	1100	petroleum	Air-3512
	1100	petroleum	DERD-2479
	1100	petroleum	DERD-2490
	1.3*	petroleum	Air-3512 and DERD-2479
Canada	1100	petroleum	3-GR-38
	1100	petroleum	MIL-O-6081B
	1100	synthetic	DERD-2487 and DERD-2497
Switzerland	1150	synthetic	DERD-2487 and DERD-2497
	1.3*	synthetic	DERD-2487 and DERD-2497
Italy	1050	synthetic	DERD-2487 and DERD-2497
Austria	1150	synthetic	DERD-2487 and DERD-2497

* Aircraft speed is given in Mach numbers.

Foreign Specifications

In the USA and England, the main countries which determine the direction
and tempo of the production development of lubricants for TRD's, specifica-
tions have been established for these oils (petroleum and synthetic), which

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define their physicochemical indicators and test methods; in addition, the establishment of specifications permits maintaining uniformity in the delivery of batches of a given type of oil.

Specifications are not unchangeable standards since corrections are systematically introduced, as are new methods of evaluating the quality or the directions for the application of oils. The latest specifications include stricter quality indicators for lubricants, which reflect the ever increasing requirements imposed upon them. Usually in the USA [95], military organizations establish specifications for lubricants for all branches of tne services, and the civil governmental organs usually accept these specifications without changes.

In the USA each specification for materials intended for use in military technology is designated by the letters MIL, after which follow letters characterizing the type of lubricant. For example, MIL-L pertains to all lubricating materials, mostly liquid oils, authorized for use in the Army; MIL-O pertains only to lubricating oils; MIL-G pertains to plastic lubricants of military type, etc. In the USA jet oil types are designated by the viscosity value of the oil at 100°F [37.8°C] with the addition of the number 1000.

The majority of lubricants for TRD's are produced by the "Shell" firm. These oils are known as Aeroshell lubricants and have their own marking. For petroleum oils after the name Aeroshell (or Turboil) a number is placed which indicates the viscosity in cs at 98.9°C; for synthetic oils this same number is multiplied by 100.

Since jet oils also have international designations, and in addition, a single NATO system marking, their complete marking is quite complex. Examples of the marking of American and English oils for TRD's are shown in Table 72 [95].

Types of Jet Petroleum Oils

Two types of petroleum oils are used for the lubrication of subsonic TRD's in the USA and England, which differ significantly from each other in operating properties[1].

---

[1]

Table 72. The Classification of Oils for TRD's Abroad

Specification	Name of Shell firm oils	NATO marking	International designation	Canadian specifi- cation
USA	petroleum oils			•
MIL-O-6081B, type 1005	Aeroshell-1 (Turboil-1)	0132	–	3GP-900
MIL-O 6081B, type 1010	Aeroshell-2	0133	OM-10	3GP-901
England				
DERD-2490	Aeroshell-3	0135	OM-11	–
ERD-2480	Aeroshell-5	–	–	–
DERD-2479/0	Aeroshell-9	0138	OM-71	3GP-431
DERD-2479/1	Aeroshell-9B	0136	OM-71	–
USA	synthetic oils			
MIL-L-7808C	Aeroshell-300	0148	–	–
England				
DERD-2487	Aeroshell-750	0149	OX-38	–

From Tables 73 and 74, where the specifications and some factual data concerning the properties of foreign petroleum oils are shown, it is apparent that types 1010 and 1005 oils are employed in the USA in accordance with the MIL-O-6081 specification, and in England oils are employed in accordance with the DERD-2490 and DERD-2479 specifications [52, 96, 97].

All these oils may be regarded as low-viscosity products, since their kinematic viscosity at 38°C does not exceed 5-10 cs; they are similar to domestic petroleum oils (GOST 6457-66).

Maxwell [98] enumerates the main TRD's in which petroleum oils are employed (Table 75) and points out that in England such petroleum oil is also employed in accordance with specifications DERD-2480[2] for oils intended for operation under Arctic conditions.

_____
[2]See p.

Table 73. Specifications in Basic Properties of American Petroleum Lubricants
for TRD's

Indicators	MIL-O-6081B, type 1005 (Turboil-1)	MIL-O-6081B, type 1005 (Turboil-1)	
		Requirements of specification	Factual data
Density ρ_4^{20}	–	–	0.893
Kinematic viscosity, cs			
at 37.8°C minimum	5.0	10.0	6.8*
at 98.9°C, "	–	2.5	2.4**
at -40°C, maximum	400***	<300	–
at -54°C, "	2600	–	40000
Temperature, °C			
flash point in open vessel, minimum	107	132	132
pour point, maximum	-60***	-57	-60
Acid No. mg KOH/g	0.1	0.1	0.01
Viscosity change after holding time of 3 hr., %			
at -54°C, maximum	3	–	2
at -40°C "	–	1	1
Oxidation-corrosion tests at 121°C for 168 hr.			
Change in mass of plates of copper, steel, aluminum alloy, magnesium alloy, cadmium-plated steel, mg/cm², maximum	± 0.02	+0.2	–
viscosity change at 37.8°C, % ....from	-5 to+20	from -5 to+20	–
Viscosity index, minimum	80	70	–
Vaporizability at 100°C for 22 hr, %	~20	~8	–

* Determined at 50°C.

** Determined at 100°C.

*** Factual data.

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Table 74. The Specifications and Basic Properties of English Petroleum Lubricants for TRD's

Indicators	Specification requirements			Factual data		
	DERD-2479/0 Turtoil-9	DERD-2479/1 Turboil-9B	DERD-2490 Turboil-3	DERD-2479/0 Turboil-9	DERD-2479/1 Turboil 9B	DERD-2490 Turboil-3
Kinematic viscosity, cs						
at 37.8°C, min.	-	-	13	70.5	70.5	14.9*
at 98.9°C, "	8.7	8.7	-	9.0	9.0	3.5*
max.	9.3	9.3	-	-	-	-
at -26°C, max.			1250			
at -40°C, "	-	-	8000	Solid		7000
Flash point, °C						
on open vessel, min	210	210	-	216	216	-
in closed vessel "	-	-	143	-	-	153-154
pour point max.	-29	-29	-46	-29	-29	-48
Viscosity index, min	105	105	71	115	115	71
Acid No., mg KOH/g maximum	0.1	0.1	0.3	0.2	0.2	0.1-0.12
Ash content, %	0.01	0.01	0.01	-	-	-
Water soluble acid and alkali content				Not Available		
Saponification No. mg KOH/g maximum	1.0	1.0	1.0	-	-	-

* The viscosity at 50°C is 7.5-7.6 cs; at 100°C the voscosity is 2.8-2.82 cs.

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The pour point of English TRD petroleum oils is 10-20°C higher than for American oils, which is explained by the different operating conditions for oils in these countries. In the Alaskan area of the USA, the air temperature extends to -55°C, whereas in England the climate is relatively mild -- a pour point for TRD oils from -30 to -40°C is fully authorized. English oils of the DERD-2479 type are already a solid mass at -40°C.

Typical viscosity-temperature curves for foreign TRD petroleum oils are shown in Figure 38. It is apparent that the American petroleum oils possess the best viscosity-temperature characteristics and that the synthetic oils (Turboil-300 and Turboil-750) have the best viscosity indices, compared to all petroleum oils.

Type 1010 petroleum oil is most frequently employed in the USA for mass-produced subsonic TRD's, where the oil operating temperature falls within the range 50-70°C and the bearing temperatures are approximately 150°C. Type 1005 oil is a special arctic oil and is employed in special cases; it contains a depressor and an antioxidation additive. Both of these oils solidify at temperatures of approximately -60°C, and their viscosity at -40°C is not more than 3000 cs and therefore they are characterized by good low-temperature properties. Multifunctional additives are introduced into American petroleum oils in order to improve their low-temperature and other characteristics.

The viscosity-temperature characteristics for domestic and foreign petroleum oils, as well as for several synthetic oils, are shown in Table 76.

In engines operating under increased temperature conditions, type 1010 oil is overwhelmingly used; this oil has a flash point 20°C higher and a vaporizability at 100°C 2.5 times greater than type 1005 oil.

In England a great deal of attention has been devoted to the high-temperature and lubricating properties of petroleum oils so that they may be used in TVD's, having highly stressed reducers. In this connection two types of oils are produced in accordance with the DERD-2479 specification: the type 2479/0 without an additive for TRD's, and type 2479/1 with a 1% additive (for high pressures), which contains sulfur and phosphorus for TVD's. Two types of oils are also manufactured in accordance with the DERD-2490 specification: without an additive and with a 0.1% addition of stearic acid, which improves lubricating properties of the oil at increased temperatures.

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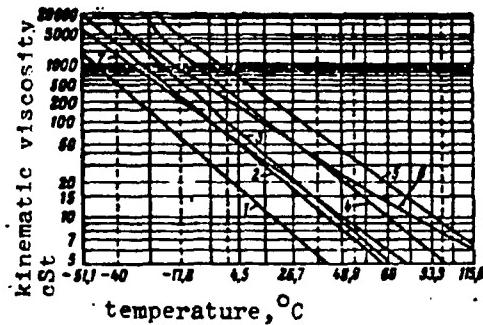
Figure 38. Typical viscosity-temperature curves for lubricants of the "Shell" firm. 1, Turboil-1; 2, Turboil-2; 3, Turboil-3; 4, Turboil-5; 5, Turboil-9; 6, Turboil-300; 7, Turboil-750

Table 75. Classification and Use of Petroleum TRD Lubricants Abroad According to Maxwell

"Shell" firm oils	Specification		Engine type
	England	USA	
Turboil-1		MIL-O-6081B, type 1005	Boeing 502 (T-50) General Electric J-47
Turboil-2		MIL-O-6081B, type 1010	Allison J-33; Allison J-35; Continental J-69 G-29; General Electric J-47
Turboil-3	DERD-2490		Rolls Royce; Dervent;
Turboil-5	DERD-2480		Havilland; Goblin
Turboil-9(9B)	DERD-2479/0; DERD-2479/1		Bristol 705; Havilland 105

In France, in addition to the Air-3512 petroleum oil already indicated, petroleum oils of the Air-3516 type with a viscosity of 10 cs at 38°C (which corresponds in properties to the type 1010 American oil) and Air-3515, with a viscosity of 3 cs at 100°C (corresponding to the English DERD2479/0 English oil) are employed.

In Canada, in addition to American oils, petroleum oils are used for TRD's in accordance with the 3-GR-38 specification (which corresponds to the American type 1010 oil). In connection with the fact that in Europe the

production of petroleum oils for TRD's is concentrated mainly in plants of the Esso and Shell firms (Turboil-1, 2, 3, 5 and 9), these oils are widely employed in such countries as Italy, Sweden, Belgium, Australia, etc. The basic properties of foreign and domestic petroleum oils are shown in Table 77 [97].

Table 76. The Viscosity-Temperature Characteristics of Petroleum and Synthetic Oils for TRD's

Specification	Type	Kinematic viscosity, cs at temperatures, ^{O}C					Pour point. ^{O}C
		-10	-20	-30	-40	-50	
Petroleum oils							
Oil by GOST 6457-66 (USSR)	-	210	585	2278	8500	--	-55
DERD-2490 (England) ----	-	215	544	1330	5800	40400	-46
MIL-O-6081B (USA)	1010	131	314	806	3000	15420	-57
Synthetic Oils							
DERD-2487 (England)	-	502	1911	3400	11590	-	-54
Diester oil (USSR)	-	165	341	845	2600	-	-60

TRD petroleum oils used in the USSR, USA and England are similar in basic properties and may be interchanged. In servicing domestic ai-craft equipped with TRD's at airports abroad (TU-104), it is permissible to use petroleum lubricants of the following types [20]: Turboil-3 in accordance with the DERD-2490 specification (England); Turboil-2 in agreement with the MIL-O-6081 specification, type 1010 (USA).

Due to incompatibility and the possibility of destroying rubber gasket materials, servicing the oil systems of Soviet aircraft equipped with TRD's with DERD-2487 and MIL-L-7808 oils is not permitted.

Bench and flight tests of petroleum oils in the USA and England in a number of supersonic TRD's, where the operating temperature of the oil attains values of the order of 230-240°C, have revealed that under these conditions a significant quantity of deposits is formed in the friction points of the engines and oil consumption increases as a result of vaporization; in addition, at increased temperatures petroleum oils display insufficient lubricating (anti-wear) properties.

Table 77. Basic Properties of Foreign and Domestic Petroleum Oils
for TRD's (Factual Data)

Physicochemical properties	Specifications or standards			
	DERD-2490 Turboil-3	MIL-O-6081B type 1010 Turboil-2	GOST 6457-66 MK-8	GOST 10323-65 MS-6
	England	USA	USSR	USSR
Kinematic viscosity, cs				
at $100^{\circ}C$	2.81	2.43	2.80	2.23
at $50^{\circ}C$	7.56	6.8?	8.30	6.10
at $-40^{\circ}C$	8000	300^	8500	1400
Temperature $^{\circ}C$				
flash point in a closed vessel	?53	132	135	143
pour point	-50	-60	-56	-57
Density ρ_4^{20}	0.870	0.89?	0.884	0.851
Acid No. mg KOH/g	0.12	0.01	0.04	0.02
Stability during air oxidation at $175^{\circ}C$ for 10 hr.				
Quantity of deposits, %	2.10	0.12	2.69	1.26
Acid No. mg KOH/g	3.46	0.69	3.66	1.49

The maximum permissible temperatures for the use of petroleum oils in TRD's are considered to be not greater than 120-130°C. Synthetic lubricants must be used at higher TRD temperatures. The possibility has been demonstrated recently of employing high-viscosity petroleum oils in highly stressed supersonic TRD's; these oils are obtained by special raw material refining and cleaning methods.

Synthetic Oils

Light petroleum oils were used successfully in foreign early-model TRD's (F-86, B-47, etc.); the operating temperatures of oils in these engines did not exceed 90-95°C. In domestic TRD's, where the maximum oil temperature at the engine output did not exceed 95-115°C, petroleum oils were also employed; the area of the application of these oils was limited to operating temperatures below 110-130°C.

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As a result of the recent shift of jet aircraft to sonic and supersonic speeds, the temperatures and operating loads in TRD friction points have increased. The maximum temperature of the bearings in supersonic TRD's may reach 315-370°C, and the average oil temperature at the bearing output may reach 175-250°C [93]. In this connection the quality requirement for lubricating oils grew, and in supercharged foreign TRD's (B-58 and F-104 types), which provided for aircraft speeds up to Mach 2, it was already necessary to employ synthetic lubricants.

When compared to petroleum oils, synthetic oils, as a rule, are characterized by less carbon formation in the engine, are less subject to vaporization and possess improved lubricating properties, particularly after the introduction of the required additives.

In connection with the rapid development of turbojet aviation in foreign countries after the end of the Second World War, the necessity arose to develop high-quality synthetic jet oils [99]. The basic requirements in the development of synthetic oils were the improvement in their high-temperature characteristics in conjunction with low vaporizability, good pumping qualities at low temperatures and high lubricating capability.

Broad research in the development of synthetic oils for TRD's has been conducted in the USA and England since 1947. Synthetic oils developed in recent years have undergone careful checking by means of bench and operating tests. The regular use of synthetic lubricants in jet aircraft began in the USA and England in 1952; subsequently, synthetic oils almost completely supplanted petroleum oils. By 1960 the demand for synthetic lubricants in the USA exceeded 8000 tons per year.

Based on a study of the quality of synthetic jet oils and the requirements imposed on them by the engines, oils used and developed for TRD's may be divided [100] into three basic groups in conjunction with their operating capabilities at high temperatures.

First Group

To the first group of oils belong synthetic oils obtained on the basis of diesters of aliphatic monohydric alcohols and dibasic acids. Representatives of this group are the first synthetic oils of the USA (the MIL-L-7808 specification with various letters) and of England (the DERD-2487

specification). These are the basic synthetic oils employed since 1952 in military and civil aircraft flying at subsonic and predominantly at supersonic speeds. Diester oils are obtained by means of the introduction into the synthetic base (mostly into di-2-ethylhexyl sebacate) of antioxidation and anti-wear additives.

The typical diester oil based on diisoctyl sebacate complies with the requirements of the MIL-L-7808 specification and has the following composition (in percent by weight) [101]:

diisoctyl sebacate	94.5
tricresyl phosphate	5
phenthiazine	0.5
Total	100

To this oil is added 0.001% by weight of siloxane as an antifoaming additive.

A large number of oils of this type [99-102] satisfies the requirements of the MIL-L-7808 specification. They represent the various diesters and aliphatic alcohols C_8-C_{10}. Usually phenthiazine is employed as an anti-oxidation additive, tricresyl phosphate as an anti-wear additive, and silicones as antifoaming agents. It is also possible to employe other additives for the purpose indicated. Sometimes additives are employed which improve the viscosity index [101].

Recently the widely employed sebacates (diisoctyl sebacate) have mostly been replaced with azelates pelargonates and even by adipates as a result of the cost rduction, although these esters are inferior to sebacates insofar as thermal stability and thermal oxidation stability are concerned.

We note [103] that octyl esters of azelaic acid complies fully with the requirements of the MIL-L-7808D specification, and pelargonic esters of trimethylol propane complies with the MIL-L-7808E specification.

Esters of dicarboxylic acids and aliphatic monohydric alcohols are among the best compounds which possess the complex of properties required as the bases for synthetic jet oils. They display satisfactory thermal oxidation stability, a high viscosity index, relatively low vaporizability and insignificant corrosive activity with respect to the majority of metals employed in TRD's. The self-ignition point of diesters is relatively high. When it is

necessary to improve the load-carrying capacity of these compounds (at the expense of an increase in viscosity), complex esters of aliphatic and dihydric alcohols with dibasic acids or polyalkylene oxides are added [103].

The consumption of diester oils in TRD's is not great; during operation at temperatures up to 175-177°C, seals of special types of resistant aviation rubber are not destroyed. Among the shortcomings of oils based on diesters we must include their corrosive activity toward lead during an extended storage period, which appears, apparently, as a result of partial diester hydrolysis. However, this shortcoming may be partially removed by the introduction of additives of the aliphatic amine type type (for example, the additive 2.6AC), which are compatible with the oils.

The properties of oils of the first group are shown in Table 78 [104].

Table 78. Properties of Synthetic Lubricants Employed ABroad (First Group)

Country and Specification	Shell firm classification	Sample no.	Kinematic viscosity at temperature, °C				Temperature °C		Acid No. mg KOH/g
			98.8	37.8	-40	-55	Pour point	Flash point in open vessel	
USA MIL-L-7808 Turboil-300*	Tur-boil-300*	1	3.5	13.6	1900	12200	-60	215	0.17
		2	3.48	-	1885	-	-60	219	0.22
		3	3.6	14.0	1900	-	-61	221	0.19
England DERD-2487	Tur-boil-750*	1	7.8	39.0	12000	100000	-57	232	-
		2**	7.42	-	10600	-	-54	239	0.17
		3***	7.43	23.4	11590	-	-59	244****	0.19

* Previously designated as Turboil-15 and Turboil-35, respectively.
** After air oxidation in the VTI device (50 hr at 150°C) the acid number was 0.26 mg, quantity of deposits of 0.04%.
*** Thermal and mechanical destruction data at 50 and 100 hr are not available; the viscosity was determined at 50°C.
**** Determined in an open vessel.

Work is continuing abroad in the improvement of the thermal oxidation stability and anti-wear properties of diester oils.

Synthetic oils based on dicarboxylic esters may operate in engines at temperatures of 150-175°C and temporarily up to 240°C [93, 94, 105]. At higher temperatures the thermal oxidation stability of oils based on diisoctyl sebacate galls (Figure 39), which is associated with its ability to absorb oxygen (Figure 40) at increased temperatures. Thus, at 250°C, the diesters absorb 22% oxygen, and at 370°C, four times as much. Therefore, oils based on dicarboxylic esters cannot provide for the operation of power-boosted TRD's, intended for aircraft flights with speeds of Mach 2, since in these engines oil operating temperatures reach 200°C and above.
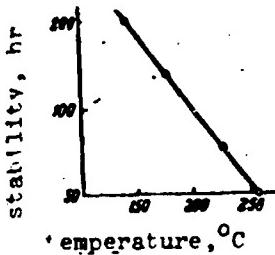
Figure 39. Temperature influence on the thermal oxidation stability of di-2-ethylhexyl sebacate (with 0.5% phenthiazine)
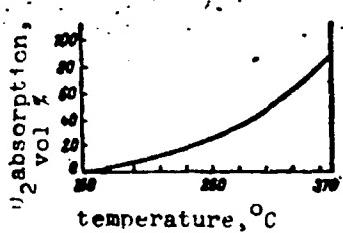
Figure 40. The influence of temperature on the ability of di-2-ethylhexyl sebacate (with 0.5% phenthiazine) to absorb oxygen

Foreign specialists point out that synthetic oils of the first group (the MIL-L-7808, DERD-2487 and other specifications) are capable of operation at

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the present time up to temperatures of 150°C and in some cases to 175-180°C
[92, 106].

Judging by data from the latest literature and reference books,
Turboil-300 oil, which corresponds to the MIL-L-7808 specification, is no
longer employed in military aircraft of the highest type.

It is still widely employed and will be.employed for a long time to come
in the engines of subsonic passenger and transport aircraft, since it provides
for reliable starting and lubrication.

Oil temperature increases during aircraft flight at supersonic speeds
not only as a result of design characteristics of the TRD, but also as a
result of the increase in flight speed. Thus, [107] at flight speeds of
Mach 2, 3 and 4, the oil temperature may reach values of 210, 315 and 420°C,
respectively (Figure 41). This is explained by significant heating of the
aircraft skin in flight as a result of air friction. Heat from the skin is
transmitted to the frame of the aircraft, and from there to the fuel and oil
tanks, to the engine and to various aircraft assemblies. According to
calculated data [108], at supersonic flight speeds of Mach 2.? the oil
temperature in the tank of a transport aircraft will be 90°C, and the
temperature at the combustion chamber injectors will reach a value of 200°C.
This in turn will be reflected as an increase in lubricant temperature. At
Mach 3 speeds the oil temperature in the tank and at the injectors is
increased to 150 and 260°C, respectively.

It is assumed that in the engine of the supersonic transport aircraft
Concord [108], developed by the English and the French, the average oil
temperature will be approximately 180°C, and that the temperature of the oil
delivered from several engine lubrication points in the pumping system will be
of the order of 285°C. It is believed that in power-boosted TRD's of the
future, oil will be in contact with air having a temperature up to 350°C.

This indicates the necessity of developing and employing a synthetic
lubricant which is significantly more stable than the oils described above.

Second Group

Oils of this type are prepared mainly on the basis of polyglycol esters
which have a more thermally stable structure than dicarboxylic esters.

Polyglycol esters are characterized by low volatility, superior viscosity-temperature properties and the capability of preventing wear in engine parts. Their thermal oxidation stability may be improved by the introduction of appropriate additives. Polyglycol esters have no active influence on metals, and insofar as cost is concerned they are less expensive than diester oils. The thermal oxidation stability of synthetic oils prepared on this base is 15-20% higher than for diester oils based on dicarboxylic acids.
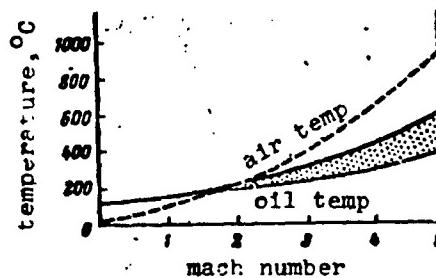
Figure 41. Incoming air and oil temperature as a function of aircraft speed

Among the more stable are also the esters which characterize the presence of the neopentyl grouping. In this structure, the carbon atoms, which are located in the β position to the ester group, are lacking in hydrogen. Oils on this base are known as neopentyl oils. Synthetic oils of improved thermal oxidation stability are also prepared on the basis of esters of trimethylol propane (neopentyl esters) and sebacic and azelaic acids.

Oils of the second group represent a wide selection of synthetic oils, the quality of which is provided for in the increased requirements of the MIL-L-23699, DERD-2497 and MIL-L-9236B specifications. These oils are employed for power-boosted (including bypass) TRD's for military and civil purposes. Thus in the engines of the American supersonic B-70 bomber, which attains speeds of up to Mach 3, oil is employed which is processed in accordance with the MIL-L-9236B specification. No significant oxidation of this oil is observed down to temperatures of approximately 210°C; the oil provides engine starting at temperatures down to -53°C.

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Oils of the second group are intended for operation within the range of 200 to 260°C; they have been produced in commercial quantities since 1963. However, the upper limit of their temperature operating capabilities has not yet been attained. These oils are promising only for the first supersonic transport aircraft of the future.

At the present time the aviation industry of foreign countries has begun to replace rapidly oils of the first group with oils of the second group.

Third Group

Oils of this group must be manufactured on the basis of new, promising chemical compounds [93]. The base of this oil may consist of pentacyclic polyphenyl esters (5P4E), the thermal stability of which is approximately 150°C higher than for the esters or oils f the second group. However, polyphenyl esters have a high pour point (4-5°C); therefore, at the present time the possibility of obtaining esters of this type in combination with other compounds is being investigated. In addition, halo derivatives of hydrocarbons, silicon compounds, chlorine-containing polyorganosiloxanes are being actively investigated. as well as high-boiling petroleum oils after supplemental processing and cleaning [109].'

Oils of the third group are intended for applications at temperatures above 260°C in TRD's of supersonic military and civil aviation, which are installed in aircraft with speeds of Mach 3 and above in the USA, England and France.

The new specification MIL-L-27502 was issued in the United States in 1965 for an oil of the third group, the operating temperature of which attains a value of 260°C. According to this specification the requirements for low-temperature properties of these oils are reduced (the viscosity at -34°C is established at 13,000 cs); nevertheless, il which satisfies the requirements of this specification has not yet been successfully manufactured (Figure 42).

Synthetic oils based on the specifications MIL-I-7808 with various letters, DERD-2487, DERD-2497 and MIL-L-9236B, etc., are manufactured and delivered to consumers in the quantities required by the Shell firm.

Synthetic oil Air-3513, which is of local manufacture, is also employed in France; it corresponds to the American oil of the MIL-L-7808C specification.

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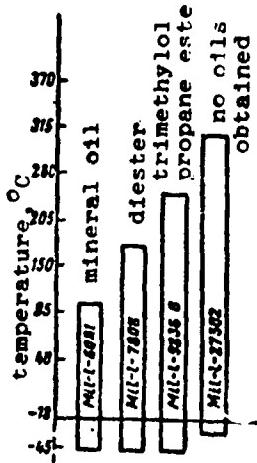
Figure 42. The temperature-range requirements of American specif-
ications for the operating capability of synthetic TRD oils

It has been reported that the first supersonic transport aircraft will
appear in 1969: in the USA with a speed of Mach 3, and in England with a
speed of Mach 2. These aircraft will be equipped with power-boosted TRD's,
for which oils of extremely high quality will be required. Since there are
still no oils in the third group, the problem of the possibility of employing
oils of the second group in aircraft of this type is being determined.

In general, liquid lubricants will not be suitable for TRD's of second-
generation supersonic aircraft. It is believed that gaseous and solid
lubricants will be employed for the lubrication of the thermally stressed
bearings of these engines.

As a result of intensive investigations abroad in recent years, the
selection and formulation of synthetic lubricants and additives for them has
increased constantly. The basic tendencies in the development of synthetic
oils of the second group abroad has been the use of so-called complex esters,
or a blend of various esters and polyalkylene esters as a base for these oils,
as well as efforts toward increasing the stability of oils by means of anti-
oxidation additives. The latter is achieved by the simultaneous use of

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several additives which in a number of cases increases their effectiveness as a result of synergism.

Specifications

Specifications for Applicable Oils

There are two very important specifications for synthetic lubricants: these are the American MIL-L-7808 and the English DERD-2487 specifications. Not only the physicochemical oil specifications, but also the methods to be employed for laboratory and operational tests (the evaluation of anti-wear properties, etc.) are included in the specifications.

Two groups of oils were developed in conformity with the minimum TRD starting temperature in the USA of -54°C and of -40°C in England: the so-called "light oils" in the USA, having a viscosity at 98.9°C of 3-4 cs and 13,000 cs at -54°C (MIL-L-7808) and the "heavy oils" in England having a viscosity at 98.9°C of 7.5 cs and 13,000 cs at -40°C (DERD-2487).

Since the English oil with a viscosity of 7.5 cs at 98.9°C is also intended for use in TVD's, the DERD-2487 specification provides for high requirements for the lubricating and load-carrying capacities of the oil and for properties to prevent bearing fatigue destruction [92]. All of these oil properties are evaluated on the IAE special test stand, in connection with which the oil must provide for test stand operation at loads not less than those imposed on a special standard petroleum oil. The load-carrying capacity of the oils, in accordance with the MIL-L-7808 specification, with a viscosity of 3.5 cs at 98.9°C must be not less than 68% of the load-carrying capacity of the standard oil.

The lubricating capacity of the oils used at the present time falls at the limit of the requirements for this specification.

A great deal of difficulty is encountered in using oil with a viscosity of 7.5 cs at 98.9°C in TRD's.

Since English oils of the DERD-2487 specification, in addition to a diester base, contain thickeners of the polymethylmethacrylate or polyester type, then a determination of viscosity stability is required; for oils which comply with the MIL-L-7808 specification, the mechanical destruction indicator is not required, since since they contain no thickeners.

The use of English and American aircraft by many international aviation lines has made it necessary to use oils of different specifications, which has created a number of technical difficulties. Therefore the demand arose for a single universal oil for all TRD's. With this purpose the MIL-L-25336 specification was developed which combined the requirements of the English and American air forces. In practice, it differs from the MIL-L-7808 specification only by an increase in oil load-carrying capacity [106]. In conformity with the MIL-L-25336 specification, the maximum operational capacity of the oil, determined on a Rider device, is 504 kg/cm in comparison with 306 kg/cm for the MIL-L-7808 specification.

However, the attainment of such an oil load-carrying capacity proved to be very difficult, since usually the additives which increase this indicator (anti-wear properties) impart to the oils increased corrosive properties or cause their thermal oxidation stability to deteriorate.

Thus, of 22 oils presented for tests in 1958, only five gave satisfactory results. In the final analysis an oil was accepted with a viscosity of 3 cs at 98.9°C which satisfied the requirements of the MIL-L-25336 specification for high-temperature and anti-galling properties.

By 1958, 14 types of MIL-L-7808 specification oils had been produced, and by 1960 there were already 32 types [102]. The requirements of the MIL-L-7808 specification were changed — six versions were developed (A, B, C, D, E and F). The D version was described in literature in 1959, the E version in 1963, and the F version in 1965 [103]. At the present time oils which are manufactured in accordance with different verions of the MIL-L-7808 specification are widely employed. The requirements of the MIL-L-7808 specification, which combine a large group of oils, are shown in Table 79 [110-113] and are examined below.

Data concerning the employment abroad of synthetic oils, corresponding to the most widely distributed specifications, are shown in Table 80 [98].

Table 79. Requirements of the MIL-L-7808 Specification

Indicator	Index			
	B	C 1955	D 1959	E 1963
Kinematic viscosity, cs				
at 98.9°C minimum	3.3	3.0	3.0	3.0
at 37.8°C minimum	-	11.0	11.0	11.0
at -54°C, maximum	13000	13000	13000	13000
Temperature °C				
flash point in closed vessel, min	196	204	204	204
pour point, maximum..............	-59	-59	-59	-60
Acid No., mg KOH/g	-	-	-	0.3
Load-carrying capacity on Rider				
device, kg/cm, minimum*	306	306	300	300
Quantity of deposits during cokabil				
ity test(315°C), mg, maximum	100	80	-	-
Corrosion tests on metal plates, mg/cm²				
at 232°C for 50 hr				
copper plate, maximum	0.47	0.47	3.0	.
silver plate, "	0.47	0.47	3.0	0.5
at 163°C, for 1 hr				
lead plate, maximum	-	0.9	0.9	. .
Oxidation-corrosion tests at 175°C for 72 hr; air delivery 5 ℓ/hr				
Change of mass of the plates, mg/cm²				
copper plate	+0.4	+0.4	+0.4	+0.4
plates of silver, steel, magnesium alloy, aluminum alloy	+0.2	+0.2	+0.2	+0.2
viscosity change at 37.8°C, %	from -5 to 15	from -5 to 15	from -5 to 15	from -5 to 15
acid no. increase, mg KOH/g, max	2.0	2.0	2.0	2.0
Swelling of type H grade A rubber after duration of 178 hr at 70°C %	-	max 12	from 12	to 35
viscosity stability after holding at -54°C				
viscosity increase after 3 hr %, maximum	-	6.0	6.0	6.0
viscosity, cs				
after 3 hr maximum	-	13000	13000	13000
after 72 hr "	-	17000	17000	17000
	-	passes	passes	passes
Vaporizability at 204°C for 6.5 hr % maximum	-	25	35	35
Precipitation formation (sludging) % maximum	-	-	5.0	3.5
Stability during storage- mass loss of lead plates, mg/cm²				
after 14 hr maximum	-	-	3.8	4.0
after 45 hr maximum	-	-	233	150
100 hr engine test by MIL-E-5009 specification	-	passes	passes	passes

*According to other data the load-carrying capacity of oils in compliance with the MIL-L-7808 specification must be not less than 68% of the standard oil.

Table 80. Use of Synthetic Lubricants in TRD'a Abroad

Oils of Shell firm	Specificationa		Engine
	England	USA	
Turboil-300	–	MIL-L-7808E	Continental 217; General Electric CJ-805; Lycoming T-53; Pratt and Whitney J-75 and J-T3D; Rolls Royce Dart
Turboil-750	DERD-2487	–	Allison 501, Blackbern; Bristol Siddley; Hasvilland Nepir; Rolls Royce Dart
Designation not established	DERD-2497	MIL-L-9236B	engine of the near future

It is apparent from the data in Table 79 that the main differences in the MIL-L-7808E specification from the preceding versions are the following:

an overall acid number indicator for fresh oil has been introduced, which must not exceed 0.3 mg KOH/g of oil;

the oil is evaluated on the Rider device at a sustained load in kg/cm on the width of the tooth (not less than 300 kg/cm) at an increased temperature.

In addition, the following changes have been made in the MIL-L-7808E specification:

a compatibility indicator has been introduced for oils corresponding to the MIL-L-7808, MIL-L-25336, MIL-L-9236 and MIL-L-6081 specifications. When mixed with the indicated oils, the MIL-L-7808E specification oil must not cause clouding, and deposits may not be greater than 0.005 ml/200 ml of oil (the deposits are determined by centrifuging in accordance with the method 3104 of the Federal Standard 791, but with no dilution by a solvent);

storage stability (lead corrosion) is determined after 2 and 7 days instead of 14 and 45 days;

an evaluation is made during the conduct of oxidation-corrosion tests of the surface of plates under a microscope with a magnification of 20 times; here there must be no pitting or visible corrosion or blackening;

the results of 100-hr motor tests are evaluated according to the following values: the motor indicator must not be more than 2.83; the increase in filter weight must not be more than 9 g/hr; oil consumption must not exceed 570 g/hr;

an ASTM [American Standard Test Method] color indicator has been introduced (maximum 3);

in place of the panel carbon formation indicator at 315°C, a precipitation formation indicator in % (sludge formation) has been introduced.

Special methods for evaluating the operating properties of oils specified in the MIL-L-7808 specification are described briefly below.

Methods of Evaluating Quality

Load-carrying capacity. This is determined on a Rider gear machine with gear rotation at a rate of 10,000 rpm, for a period of 10 min at each load, with a gear input oil temperature of 74°C. The gears must withstand a load of not less than 306 kg/cm; here the scored area on the operating surfaces of the

teeth must not exceed 22.5%. During acceptance tests eight determinations are made; the average value must be not less than 68% of the load sustained by the standard oil. It is assumed that if the oil withstands the load on the Rider device, then it will operate successfully in engines.

Tendency toward the deposit of residues. This indicator is determined by the "coke formation on a panel" method by means of spraying oil from a shaft equipped with a toothed rack on a panel which has a temperature of 315°C for an 8-hr period. The quantity of coke must not exceed 80 mg. The results obtained with this method agree poorly with the motor tests [110]; therefore, a combined test method is most promising -- a combination of testing for cokability on a panel at 315°C with a test for sludge formation according to the Wright Brothers Research Center method. According to this method 24 ℓ of oil are pumped through a gear box for 25 hr and through a filter with an aperture of 100 ι and a rubber hose of Buna N rubber at a rate of 2-3 g/min.

The results of these tests (the filter is weighed before and after pumping) are combined and the number of deposits is determined in g, which characterizes cokability at 315°C on the panel and sludge formation on the WADC test stand. This method was included in the MIL-L-7808B and E specifications instead of the method of determining cokability.

Corrosive properties. These are determined by means of conducting three laboratory tests of the oil at various temperatures both with and without air delivery:

1) lead plates are maintained in the oil at 163°C for a period of 1 hr;

2) plates of five metals (copper, magnesium, iron, aluminum and silver) are maintained in oil for 72 hr at 175°C in an air current (this test is included in the oxidation-corrosion method);

3) copper and silver plates are submerged in oil for 50 hr at 232°C.

Under the conditions indicated, the oil must not cause corrosion of the metals, and its physicochemical properties must undergo no changes.

Storage stability. According to a stringent method of determining oil stability during storage [92], specimens of the oil being tested (3.0 ℓ each) are held in cans in a thermostat at 85°C with lead plates; the corrosive properties of the stored oil samples are determined after each 7 days of

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storage. Corrosion on the lead plates must not exceed 3.8 mg/cm^2 after 14 days, or 23.3 mg/cm^2 after 45 days of storage. The results obtained by this method agree very well with the results of changes in oil during storage under depot conditions.

Volatility or vaporizability. This indicator is determined indirectly by the flash point (which must be not less than 204°C) and directly by means of vaporizing and oil specimen for a period of 6.5 hr at 204°C in a special test tube. Oils in which vaporization does not exceed 35% by weight are considered to be acceptable.

Viscosity stability. The oil is maintained for three hours at -54°C, after which viscosity is determined at -54°C. The results of two determinations after three hours holding time must not differ by more than 6% from the initial viscosity value and in both cases must not exceed 13,000 cs. The viscosity of the specimen after a holding time of 72 hr at -54°C must not exceed 17,000 cs.

Foamability. Air is passed through oil at 24, 93 and 24°C for a period of 5 min. Foam volume must be not more than 100, 25 and 100 m , respectively, and the time required for foam disintegration, 5, 3 and 5 min, respectively.

Engine test. In addition to laboratory tests in accordance with the MIL-L-7808 specification, 100-hr operational capability engine tests are required (the MIL-E-5009 specification).

Oil specimens are tested in J-57-19 and J-57-29 engines. The temperature of the oil is maintained at a level of 149°C ± 3°C; the test consists of 20 cycles, each of which is 5 hr in duration, under conditions stipulated in a special chart (variable loads, stops, boost, etc.). Before each cycle a clean, weighed filter is installed, and after each 5-hr period the change in its weight and the oil consumption are determined.

The performance number of the oil is determined in accordance with the special scale shown below, by comparing the condition of various parts and the most characteristic friction points of the engine with their condition after operation with a standard oil:

Performance number	Condition of engine parts after operation with the oil tested in comparison with operation with a standard oil
4	considerably better
3	somewhat better
2	identical
1	somewhat worse
0	considerably worse

A list of standards for test methods, included in the MIL-L-7808 specification, is shown in Appendix 2.

Specifications for Prospective Oils

The MIL-L-9236 specification was published in the USA in 1952 for synthetic high-temperature lubricants for TRD's of the near future [92]. These oils are characterized by high antioxidation and anti-wear properties.

Basic factors in the evaluation of the quality of the high-temperature oils during special tests are the temperature of the oil being tested in the tank and the bearing temperature where the oil is being tested. At first, the MIL-L-9236 specification provided for 100-hr bench tests of the oil at a tank temperature of 260°C and at a bearing temperature of 400°C. Since not one of the oils developed past these conditions, in 1956 this specification was replaced by the MIL-L-9236A specification, in which the oil temperature in the tank was reduced to 204°C and the bearing temperature was not limited.

Since the oils did not pass these specifications as well, the temporary MIL-L-25968 specification was introduced in the USA with requirements that were reduced even further.

Oils were successfully obtained in 1959 which were similar in quality to the MIL-L-9236A specification, since the specification had been accepted in a somewhat changed form. A later version was published [92] in 1960 -- the MIL-L-9236B (Table 81) specification, in agreement with which the oil was required to have good low-temperature properties, relatively low viscosity, satisfactory characteristics during engine tests and satisfactory characteristics on the EDCO bearing test stand. Tests on this stand were conducted at

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a tank oil temperature at the input of 204°C and with a stable bearing temperature below 260°C.

Table 81. Basic Properties of High-Temperature Synthetic Oils According to Specifications of the USA

Indicators	Specifications				
	MTL-L-9236	MIL-L-9236A	MIL-L-9236B	MIL-L-27502	MIL-L-23699
kinematic viscosity, cs					
at 204°C, minimum	–	3.0	1.0	1.0	–
at 98.9°C, minimum	10.0	Optional	–	–	5.6
at 37.8°C, minimum	3.5	"	–	–	–
at -40°C, maximum	–	–	–	–	13000
at -54°C, maximum	13000	–	–	–	–
viscosity stability after holding -54°C: viscosity increase after 3 hr, %, maximum	–	–	6		–
temperature, °C flash point, minimum	288	260	218	260	1
pour point, maximum	-59	Optional	-59	-43	-54
foamability test			Passes		
vaporizability, %, maximum	5	5	15	10	"
swelling of rubber, %	–	–	12-35	12-35	12-35
load-carrying capacity on a Rider device with respect to standard oil, %, minimum	–	–	56	100	414*
thermal oxidation stability test on bearing test stand	Passes	–	Passes	Passes	–
compatibility test with other oils	"	Passes	"	"	Passes
100-hr engine test	–	–	–	"	–

* In kg/cm.

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Table 82. Basic Requirements of English DERD-2487 Specification (Third Version) and DERD-2497 Specification for Synthetic Oils

Indicators	DERD-2487	DERD-2497
Kinematic viscosity, cs		
at 204°C, minimum	-	2.0
at 98.9°C, maximum	7.5	8.5
at 37.8°C, "	39	
at -40°C, "	13000	13000
Viscosity stability after holding at -54°C; max viscosity increase after 12 hr, %	5	Optional
Temperature, °C		
flash point, minimum	216	260
pour point, maximum	-50	-
self-ignition, minimum	-	385
Foamability test	passes	passes
Vaporizability, %	indicated at 200°C	
Load-carrying capacity* on IAE friction machine at 2000 and 6000 rpm	no less than standard oil	
Swelling of rubber at 70°C during 168 hr, %	-	15-25
Thermal stability* viscosity change at 37.8°C, %	from -10 to 20	from -10 to 25
Oxidation-corrosion tests*		
weight change of plates, g/cm², of copper, silver, steel, cadmium-plated steel, magnesium alloy, aluminum alloy, silver-plated steel, titanium	±0.2	±0.2
viscosity change at 37.8°C, %	±5	from -5 to 10
acid no. increase, mg KOH/g maximum	0.5	2.0
Load tests at 280°C	passes	-
Mechanical stability (shearing stability) - viscosity change at 37.8°C, %, maximum	±5	Optional
Uniformity test at temperatures from -54 to 280°C	passes	-
Compatibility test with other oils at temperatures from -54 to 280°C	passes	-
100 hr engine test	-	passes

* In accordance with the DERD-2497 specification, the test conditions are more stringent. (See p. 201)

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The load-carrying capacity of the oil as measured on the Rider machine at 204°C, according to the MIL-L-9236B specification, must be not less than 56% of the load-carrying capacity of the standard oil. At this same temperature, toothed gears must withstand a deformation fatigue test. The oil must also pass tests on the Wright Brothers Research Center bearing test stand (50 hr, tank oil temperature 218°C, and bearing temperature of 260°C).

The English DERD-2497 specification for high-temperature oils of the near future was published for the first time in 1959. The physicochemical property requirements for oils in accordance with this specification are similar to the requirements outlined in the DERD-2487 specification; however, the DERD-2497 specification provides for enhanced thermal and thermal oxidation stability of the oils (Table 82), and also for enhanced anti-wear properties [92].

During tests of the anti-wear properties of these oils on the IAE test stand when the load-carrying capacity of the oil tested is equal to 100% of the load-carrying capacity of the standard oil, it may be equated to a load of 540 kg/cm on the Rider device, which permits comparing the results of the oil tests on these two test stands.

The special methods for evaluating the qualities of high-temperature oils for TRD's, specified in the MIL-L-27502, MIL-L-9236B and DERD-2497 specifications, are briefly described below.

Methods of Quality Evaluation According to U.S. Specifications

Viscosity stability. Oil viscosity after a holding time of 3 hr at -54°C must not exceed 21,000 cs according to the MIL-L-9236B specification and 13,000 cs according to the MIL-L-27502 specification; after a holding time of 72 hr, the figures are 24,000 and 17,000 cs, respectively.

Rubber swelling. According to the MIL-L-9236B specification, rubber is maintained in the oil for a period of 72 hr at 204.4°C, and in accordance with the MIL-L-27502 specification, for 72 hr at 260°C, and for 168 hr at 70°C in accordance with the MIL-L-23699 specification.

Vaporizability. Vaporizability in accordance with the MIL-L-9236B specification is determined as usual at 204.4°C, and in accordance with the MIL-L-27502 specification, under more stringent conditions -- at 260°C.

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Bearing stability tests. MIL-L-9236B specification oils withstand tests at an oil temperature of 234°C and a bearing temperature of 274°C; the duration of the test is 50 hr MIL-L-27502 specification oils are tested for a period of 100 hr at an oil temperature of 274°C and a bearing temperature of 329°C.

Load-carrying capacity. Tests for load-carrying capacity of oils on the Rider device for MIL-L-9236B specification oils are conducted at an oil temperature of 204°C in stead of 74°C.

Quality Evaluation Methods According to English Specifications

The foamability. Foamability is determined at three temperatures, just as in the MIL-L-7808 specification, and foam volume must not exceed 100, 25 and 100 ml, respectively, and the period of existence of the foam must not exceed 5, 3 and 5 min, respectively. There is an indication [52] that at the present time high-viscosity DERD-2487 and DERD-2497 specification oils will not be limited insofar as foamability is concerned.

Load-carrying capacity. This indicator on the IAE test stand for DERD-2487 specification oils is determined at identical temperatures for the standard and tested oils, equal to 110°C, and in accordance with the DERD-2497 specification, at a standard oil temperature of 110°C, and a test oil temperature of 200°C (increased requirements).

Thermal stability. The oil is heated in a nitrogen atmosphere, and the process of heating consists of four cycles of 6 hr each. The temperature is raised to 280°C according to the DERD-2487 specification and 325°C according to the DERD-2497 specification. After heating, the viscosity is determined at 37.8°C.

Oxidation-corrosion tests. The oil is oxidized by means of a current of air at a rate of 12 ℓ/hr according to the DERD-2487 specification for a period of 22 hr at 140°C and for a period of 24 hr at 260°C in accordance with the DERD-2497 specification.

Mechanical destruction stability. The criterion for evaluating the tendency toward mechanical destruction is the viscosity change (in %) at 37.8°C after oil destruction by means of a 250-cycle passage of the oil through the jet of a diesel injector at a pressure of 145.7 kg/cm^2 and a

temperature of 100°C. The oil is subjected on the test stand to the pump and injector for a period of 168 hr. The viscosity at 98.9°C must not change by more than 2%.

Load test. According to the DERD-2497 specification,. the oil is required to operate satisfactorily in in a loaded high-speed bearing with an outer race temperature of 325°C and an oil input temperature to the bearing of not less than 200°C.

Several companies which produce TRD's in the USA and England have their own specifications for lubricants for these engines. Among these specifications, for example, are Allison EMS-359, Pratt and Whitney PWA-521A and several others.

These specifications do not differ fundamentally from those examined above and are, in essence, the companies' modifications which take into consideration requirements for oil quality with respect to design peculiarities of the TRD's of a given firm. Specifications of the firms include original methods of determining the physicochemical properties of oils, especially antioxidation and anti-wear properties.

The greatest differences are observed under conditions involving laboratory tests of oxidation-corrosion oil tests (Appendices 3 and 4).

Footnotes

1. To p. 174. Recently the employment of petroleum oils in England has been limited.

2. To p. 175. Turboil-5.

CHAPTER FOURTEEN

THE BASIC DIRECTIONS IN THE DEVELOPMENT OF FOREIGN SYNTHETIC OILS FOR TURBOJET ENGINES

It has already been noted that synthetic oils abroad are based on products which are among the most diverse classes of organic compounds. Thus, known TRD oils are based on dibasic acid esters, polyglycol esters, neopentyl alcohol esters, polyphenyl esters, etc. As components for TRD oils, ortho-silicate acid esters, tetraalkylsilanes, tetrasubstituted carbamides, several heterocyclic compounds, etc., have been used. The preparation, overall properties and possible regions of application of the organic compounds indicated have been described in literature [52].

A short survey is given below of the most interesting research in the area of the development of foreign synthetic TRD oils during recent years, compiled on the basis of the material in American and English patents, published in the last 5-6 years.

Oils of the First and Second Group

Methods of preparation, formulation and the properties of oils of these two groups have much in common; therefore, these two groups will be examined together.

The following synthetic TRD lubricants have been developed:

a mixture of methyl-2-ethylhexyl diesters of polyglycols, supplemented by additives phenylnaphthylamine, a mixture of alkylamino acid, alkylphosphate with alkyldihydrophosphate, tricresylphosphate, quinizarin, and a dimethyl-siloxane polymer [114];

oil produced by means of introducing into a diester of dicarboxylic acid (C_4-C_8) tricresyl phosphate, phenthiazine and dialkyl selenide and which comply with the majority of the requirements of the MIL-L-7808A specification [115];

oils have been obtained from a diester base and with additives of two
types: antioxidation (phenthiazine or dialkylselenide) and anticorrosion
types (azimino-benzene or benzimidazole or pyrazole, etc.) [116];

oils with improved thermal oxidation stability and good viscosity-
temperature characteristics, consisting of di-2-ethylhexyl sebacate, in which
a polymer of an azelaic acid polyester and propanediol have been introduced in
order to improve the viscosity index. A diphenyl ester may be used as the
synthetic base within the composition indicated. According to tests for
thermal oxidation stability in accordance with the DERD-2487 specification,*
the viscosity of the oil after 24 hr was reduced by 3% in all, whereas without
the polyester polymer additive the viscosity was reduced by 22-50%. The oil
also contains the antioxidation additive phenthiazine [117];

a stable lubricant of pentaerythritol etraester with trimethyl acetic
acid. The oil contains diphenylamine and phenthiazine [118];

oil based on a polyester (one of several trimethylpropane esters with
mono- or polycarboxylic acids), to which are added diphenylamine or its alkyl
(or aryl) substitutes [119]. The oil is intended for high-temperature TRD's;

a diester oil which satisfies the requirements of the MIL-L-7808C
specification, obtained by esterification of pelargonic acid by highly
branched aliphatic or cyclic diatomic alcohols [120];

oil from one or several trimethylpropane polyesters with diatomic
alcohols or their blends. The oil contains alkylphenthiazine and the number
of carbon atoms in the alkyl group is not more than 15 [121];

oil consisting of a blend of dicarboxylic acid esters and polyalkylene
glycol esters (dual-component) [122];

oil on a diester base, in which titanium-containing additives (to improve
the load-carrying capacity) and nitrogen-substituted para-aminophenol have
been introduced [123];

oil on a diester base, containing phenthiazine and aminopyridine in
various quantities, which in this ratio possesses a synergistic effect. The
oil is capable of operation up to 205-210°C [124];

oil on the basis of diesters with an improved load-carrying capacity as a
result of the introduction of an additive containing silicon [125], or a
substituted hydroxyethane halogen [126];

oil from a pentaerythritol ester (or from some other polyatomic alcohol)
with a monobasic acid, containing not more than five carbon atoms in a chain.

Two antioxidation additives are introduced into the base: substituted α- or β-phenyl amine and substituted phenthiazine. The oil is stable to 220°C [127];

oil on the basis of a diester of dicarboxylic acids and a polyester which acts as a thickening component [128];

oil from an ester base (a mixture of diester oil and complex essential oil, obtained by the reaction of monoatomic or diatomic alcohol with a dibasic acid); two antioxidation additives of the dephenylamine type are used, or one additive of the dephenylamine type in the other of the naphthylamine type. The oil is resistant to the effects of high temperatures [129];

oil based on a diester, into which three antioxidation additives are introduced 1) phenthiazine or its derivatives; 2) a chlorinated phenol compound C_6-C_{18}, for example, chlorophenol; 3) an aliphatic amine C_2-C_{30} or a heterocyclic amide. The oil is resistant to the effects cf high temperatures (oxidation for a period of 45 hr at 175°C) [130];

oil on the basis of a pentaerythritol ester and a monobasic acid supplemented with two synergistically effective antioxidation additives (N-phenyl-1-naphthylamine and a blend of dipyridine amine, aminoquinoxine and aminopyridine), which increase the induction period of oil oxidation from 5 to 305 min [131];

oil on a diester basis, to which are added products which form as a result of compound reactions, one of which contains a quinone group (benzoquinone), and the other is a thio- or dithiophosphoric or dithiophosphinic acid. Upon the addition of 3% of this component to the oil, bearing wear is reduced by ten times, and the increase in viscosity (which occurs as a result of oxidation) is reduced from 58 to 26% [132].

The thermal oxidation stability of synthetic oil is improved by the introduction of alkyl derivatives of phosphoric acid [133], of a barium salt of a nitrogen-containing amide (C_8-C_{12}) hydroxy acids [134], and by the introduction of various substituted amines, diamines, phosphines, phenthiazines, silines, aminopyridines, diphenyl compounds, etc. [135-142].

It is apparent from foreign patents of the year 1965 which pertain to the development of synthetic oils for TRD's that investigators are devoting most of their attention to obtaining lubricants which are oxidation-resistant at high temperatures. This tendency is being followed in the selection of oil

bases and in the complex of additives which supplement these oils. Neopentyl esters are widely employed as basis for oils of this type, since diester oils comply with the requirements of superconic TRD's insofar as antioxidation properties are concerned only for a short period of time.

Oil based on triesters of trimethylol propane satisfies the requirements of the MIL-L-9236 specification for high-temperature gas turbine oils, but some of the indicators (viscosity at 260°C, flash point, etc.) do not agree with the requirements of the English DERD-2497 specification. Therefore an oil was proposed based on a complex ester obtained by the reaction in specific ratios of trimethylol propane, monobasic and dibasic acids (for example, caprylic and sebacic). A dual-component antioxidation additive of the amine type [143] is introduced into the base.

In order to increase the viscosit· f oil based on a diester of dicarboxylic acid and monoatomic alcohol, a copolymer (with a molecular weight of approximately 200,000) is introduced, obtained by the reaction of an unsaturated nitrogen-containing monomer (for example, N-vinyl-pyrolidine) with one or several esters of acrylic or methacrylic acids. acids. Components of the oil are poly-oxyalkylene glycol, a complex ester, and also phenthiazine or alkylphenthiazine (as antioxidation additives) [144]. This oil fully satisfies the requirements of the DERD-2487 specification.

The load-carrying capacity of synthetic oils is improved by the introduction as an additive of a partial ester (monoester or diester) of tricarboxylic (for example, tricarboxylic propane) acid and monoatomic alcohol [145]. With the introduction of 1% of this additive into diisoctyl sebacate oil, the load sustained by the oil on a Rider device is increased by 12%.

A method was proposed for improving the thermal stability and the stability of the viscosity-temperature properties of oil prepared on the base of a complex ester of trimethylol propane and a mono- or dibasic acid. The ester is heated to 250-300°C for a period of 4 hr in an atmosphere of inert gas and the volatile products which form are boiled off. Phenthiazine or diphenyl phenthiazine is added to the oil.

After testing for a period of 6 and 24 hr (according to the requirements of the DERD-2497 specification), the viscosity at 98.9°C for thermally

processed oil was changed by 3 and 6%, respectively; for a fresh complex ester, the viscosity was changed by 25 and 29%, respectively [146].

A synthetic lubricant which satisfies the requirements of the DERD-2487 specification with respect to thermal stability consists of a blend of diesters and polyalkylene compounds (for example, polyalkylene glycols), to which are added up to 1.5% thiophosphates or sulfonated products of their processing. The oil contains antioxidation and anticorrosion additives and is thermally stable up to 325°C [147].

A synthetic lubricant with good high-temperature properties has been developed which complies with the requirements of the MIL-L-7808C, MIL-L-25336A and MIL-L-9236A specifications. The base of the oil is a homogeneous base component blend (selected in a specific ratio) which is a neutral polyester obtained by the reaction of a saturated monoatomic primary alcohol and carboxylic acid, and a polymerized ester (molecular weight 100,000) of acrylic or methacrylic acid with monoatomic saturated alcohol. An antioxidant (alkylphenthiazine or alkylphenylamine) and a copper corrosion inhibitor [148].

An oil has been proposed which is similar in purpose and in composition to the preceding one [149], but a polyalkylene glycol is recommended for the second component.

The Anglo-American firm "Castrol Limited" has developed and supplied the high-quality oil Castrol-98 and Castrol-3C, intended especially for the lubrication of TRD and TVD main bearings and gear housings. At the present time these oils are generally recognized, widely employed, and therefore deserve a detailed description.

The high-viscosity oil Castrol-98 (viscosity at 99°C 7.8 cs, at 38°C 36.1 cs, at -40°C 11,700 cs) is prepared on a base of 66% diisoctyl sebacate, and 28% polyglycol ester; the remainder consists of additives, which improve its antioxidation properties (dioctyl phenylamine, etc.), lubricating capability (calcium sulfonate), and which reduce corrosive affect, etc. This oil, which complies with the DERD-2487 specification, is capable of operation up to a temperature of approximately 180°C. The combination of a high-quality base with a complex of effective additives provides (according to firm's data) an extended period of service in engines (500 hr and above).

Castrol-98 oil is widely employed in such gas turbine engines as the Dart (the aircraft "Viscount," "Herald," "Comet," "Fokker 27," "Fairchild 27"), the Avon engine (the aircraft "Comet," "Caravelle"), the Tyne engine (the "Vanguard" aircraft), the Spey engine (the "Trident" aircraft), etc.

At the present time Castrol-98 oil is used by 15 airlines in France, Austria, England, Canada, New Zealand, Morocco, the Sudan, Tunisia and other countries. This oil is supplied with the designation OX-38 to England, France, the Federal Republic of Germany, India, Italy, Kuwait and the Netherlands [150].

Castrol-3C oil, according to the firm's data, is similar to Castrol-98, but differs from it by lower viscosity (at 99°C, 3.8 cs; at 38°C, 15.3 cs; and at -40°C, 2140 cs). The base is diisoctyl sebacate (95%); the additives are the same as for Castrol-98 oil.

Castrol-3C oil is capable of operating up to 180-185°C and complies with the requirements of the MIL-L-7808 specification. It is employed in the engines Avon (the "Carabelle" aircraft), Pratt and Whitney JT3D (the "Boeing 720" and "Boeing 707" aircraft), Pratt and Whitney JT8D (the aircraft "Boeing 727," "Douglas DC-8"), General Electric (the "Convair 990," "Coronaco") etc. According to reference data, this same firm also manufactures Castrol-205 (MIL-L-23699 specification), intended for operation at temperatures up to 200-210°C [150]; this pertains to oils of the second group.

The quality of Castrol-98 and Castrol-3C oils is investigated according to the latest methods employed abroad for these purposes. The properties of Castrol-98 and Castrol-3C oils and the testing methods are shown in Appendix 5.

Oils of the Third Group

The search is being carried out actively abroad for products which will make it possible to obtain thermally stable oils which make up the third group. We shall note several of the most promising of these products.

In order to obtain thermally stable oils it has been proposed [151] to employ esters of neopentyl polyols (esters of trimethylol propane, pentaerythritol and other similar alcohols). However, with good biscosity properties, low pour points and satisfactory lubricating properties, the limit of the operating capability of these materials does not exceed 200-220°C.

Therefore, oils based on neopentyl polyalcohols must be regarded as high-quality oils of the second group, rather than as oils of the third group. However, these oils have not yet been exhaustively investigated.

Polyphenyl esters have low volatility, low toxicity, cause no metal corrosion and are highly stable. Thus, during a test for oxidation corrosion at 315°C, their viscosity did not increase by more than 7%, and metal corrosion was practically nonexistent. In lubricating properties, polyphenyl esters are somewhat better than petroleum oils, but are inferior to di-2-ethylhexyl sebacate in the temperature range 100-200°C. However, at 316°C they surpass diesters insofar as this characteristic is concerned [154]. The first attempts to employ these as lubricants goes back to 1959. At the present time the investigation of polyphenyl esters continues [155].

High molecular weight tatraalkylsilanes are being investigated as basis for high-temperature lubricants. These silicones differ from known poly-siloxanes in that their alkyl radicals represent a long hydrocarbon chain, and therefore such compounds have the characteristics of paraffins.

The properties of dialkylsilane cyclohexanes [156], dialkyl-di-dodecylsilanes and trialkyl-di-dodecylsilanes [157] have been carefully studied in recent times.

Tetraalkylsilanes are characterized by satisfactory anti-wear properties and are thermally stable to approximately 370°C, but they require that an inhibitor be added, since at 260°C they oxidize after a period of 24 hr and may leave deposits.

High-temperature oils prepared on a base of silicone fluoroesters [158] deserve attention. These oils are capable of withstanding high temperatures, pressures and radiation. Silicone fluoroesters combine the merits of silicones, which are characterized by resistance to high and low temperatures, and to chemically corrosive products, and fluorohydrocarbon substances, which are distinguished by their high lubricating properties. They are resistant to oxidation up to 260°C and preserve fluidity down to -54°C. Oils prepared on a base of these compounds satisfy the requirements of the MIL-L-9236B specification. Fluorinated esters of pyromillitic and camphoric acids which are stable up to 320 and 285°C, respectively, satisfy the same requirements,

according to a report by Ballard and Sommers [159]. However, the pour point of these esters is significantly higher (-32°C) than for sebacic acid diesters (-60°C).

Various ferrocene derivatives, urea, heterocyclic compounds (derivatives of borazene, phosphorus nitrile chloride, methylpyrazine), aromatic amines, etc. [52].

The use of special petroleum oils as high-temperature TRD oils is quite promising and described in detail below.

The high-temperature petroleum oils of the near future present some interest. Up until the present time it has been believed that petroleum lubricants in engine friction points and mechanisms at high temperatures (300-350°C) were not suitable in connection with insufficient thermal oxidation stability and high vaporizability. Research in recent years has revealed the error of this view. Thus, it has been pointed out [108] that together with polyphenyl esters, halo derivatives of carbons and silicons, several hydrocarbons possess the highest thermal stability, in particular, high-boiling petroleum oils after their supplementary processing and cleaning.

Data concerning the thermal stability of various organic compounds are shown below [108]:

	Decomposition temperature, °C
hydrocarbons	340-370
organic esters	230-290
phosphoric acid esters	200-260
polyglycol esters	260-290
polysiloxanes	315-370
halo derivatives of hydrocarbons	315-400
polyphenyl esters	425-480
polybutylenes	230-260
polymethylcrylates	2C0-230

Therefore, specific petroleum oils and their fractions may also be employed together with petroleum oils in the lubrication of high-temperature TRD's. A complete change in the structure of such oils and special cleaning methods make it possible to obtain petroleum oils which in thermal oxidation stability and in other properties surpass synthetic oils based on diesters.

The influence of deep cleaning of petroleum oils on their thermal oxidation stability is shown in Figure 43. Oils were tested for oxidation by passing air through 100 ml of oil at a rate of 5 l/hr at 175°C in the presence of plates of copper, iron, aluminum and magnesium [108].
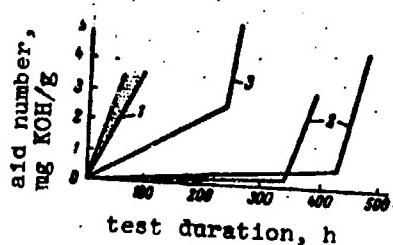

Figure 43. The influence of the deep cleaning of petroleum oil on oil oxidation stability: 1, Petroleum oil cleaned as usual and with oxidation inhibitors; 2, Deeply cleaned oils with dithiourea; 3, Synthetic oil according to the MIL-L-7808 specification with phenthiazine

Table 83 shows data concerning the tendency of synthetic oils (MIL-L-7808 specification) and deeply cleaned petroleum oils toward coking.

Table 83. Cokability of Synthetic and Petroleum Oils at High Temperature

Oil	Cokability, mg/g	
	at 315°C	at 370°C
synthetic (MIL-L-7808 specification)	30.0	2100
deep-cleaned petroleum oil	200.0	400

From the data in Table 83 it is apparent that at 370°C, synthetic oils are significantly inferior to petroleum oils, insofar as this indicator is concerned.

Tests for thermal oxidation stability and corrosive activity, accomplished for a 24-hr period at 260°C (Table 84), revealed that intensively cleaned petroleum oils are more resistant to the effect of high temperatures than oil based on di-2-ethylhexyl ester of sebacic acid.

As a result of deep cleaning, the substances containing nitrogen, oxygen, sulfur, as well as low-stability compounds which have a tendency toward the formation of deposits and other products of oxidation are removed from

petroleum oils. In addition, such cleaning permits obtaining oils with a high viscosity index.

Table 84. Corrosive Activity and Acid Number of Deeply Cleaned Petroleum Oil at 260°C

Indicator	Oil	
	Synthetic MIL-L-7808	Deeply cleaned petroleum oil
corrosion, mg/m^2, on metals		
copper	0.6	
magnesium	41.0	0
iron	1.5	
aluminum	0	
acid number, mg KOH/g	6.1	1.7

Hydrogenation, acid cleaning, adsorption cleaning and a combination of these processes are employed for the deep cleaning of petroleum oils. As a result of such processing, the content of undesirable polar components, insoluble and unstable compounds is changed.

Hydrogenated petroleum oils present a great deal of interest as a base for the preparation of high-temperature oils. The process of hydrofining is accomplished with catalysts which facilitate the saturation of aromatic hydrogen rings, and the splitting of cyclic structural rings and isomerization. During such hydrorefining, sulfur is removed from the thiophenic rings and low-cyclic compounds of isomeric structure are formed with a high viscosity index. Hydrorefined oils differ from oils of ordinary solvent refining by a higher content of noncondensed cycloalkanes and a lower aromatic hydrocarbon content (1.5 instead of 11%). Therefore, hydrorefined oils have better thermal oxidation stability and better compatibility with antioxidation additives. Noninhibited hydrorefined oil is 2-3 times more stable than noninhibited selectively refined oil. For example, the cokability of hydrorefined oils after tests on a panel at 371°C for a period of 8 hr was 40-50 mg, and for oil refined in the usual manner, 90 mg.

In addition to hydrogenation and hydrocracking, the manufacture of high-temperature petroleum oils also involves the polymerization of olefins, the alkylation of aromatic hydrocarbons and the isomerization of paraffin hydrocarbons which permits the manufacture of oil with a high viscosity index in a low pour point [160].

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In connection with all of the methods described above for the chemical processing of oils, various supplementary methods for their physicochemical cleaning are also employed -- deep dewaxing, adsorption cleaning and fractional composition compression.

The viscosity-temperature properties of deeply cleaned petroleum oils are shown in Table 85, and data concerning their compatibility with antioxidation additives are shown in Table 86.

Table85. Viscosity-Temperature Properties of Oils Obtained by Various Methods of Deep Cleaning of the Petroleum Base

Method of manufacture or cleaning of oil	Viscosity, cs		Viscosity index
	at 98.9°C	at -40°C	
paraffin hydroisomerization	3.31	1,590	139
deeply cleaned and deeply dewaxed oil	4.05	6,870	102
olefin polymerization	6.23	10,500	129

Table 86. Relative Oxidation Stability of Deeply Cleaned Petroleum Oils with an Additive (1% by weight)*

Oil	Additive	Stability*
paraffin	phenyl-α-naphthylamine	100
paraffin	dithiourea	305
naphthenic	phenyl-α-naphthylamine	100
naphthenic	dithiourea	350
hydrogenated polyolefin	phenyl-α-naphthylamine	260
hydrogenated polyolefin	dithiourea	240

* Oxidation was accomplished according to the method specified in the MIL-L-7803 specification in the presence of copper, steel, aluminum and magnesium catalysts. The oil was considered to be stable up until the moment of a sharp increase in the acid number.

Attention is directed to the high effectiveness of the antioxidation additive based on ditniocarbamate up to temperatures of the order of 260°C. At higher temperatures dithiocarbamate breaks down with the formation of metal sulfide which is insoluble in oil.

Phenyl-α-naphthylamine is also rather effective in deeply cleaned oils, but it is less stable under the influence of light; therefore, the oil may show traces of insoluble sludge, which is typical for a number of nitrogen-containing additives.

A study of paraffins, polyolefins and petroleum oils [161-172] has revealed that the basic influence on the compatibility of the base oil and the antioxidation additives is the content in them of polar substances and unsaturated compounds. The chemical group composition of petroleum oil (the content of paraffins, naphthenes and other hydrocarbons) has less influence on the additive compatibility than the compounds indicated. The properties of dewaxed and deeply cleaned oil (MLO-2557 or MLO-60-294 specifications) are shown below:

```
kinematic viscosity, cs
  at 98.9°C                                              3.2
  at 37.8°C                                              14.4
  at -40°C                                               3,210
  at -54°C                                               22.900
viscosity index                                          94
vaporizability at 204°C for 6.5 hr, %                    59.2
temperature, °C
  flash point                                            199
  pour point                                             -59
decomposition of the base oil without additive           357
  self-ignition point                                    390
acid number, mg KOH/g                                    0.001
deposit formation, %                                     0.01
molecular weight (calculated from boiling point)         328
thermal oxidation stability at 175°C according to
  requirements of the MIL-L-7808 specification
  change in weight of metals, mg/cm$^2$                  ±0.05
  viscosity increase, %                                  14
  acid number increase, mg KOH/g                         1.2
anti-wear properties, determined on four-ball
  friction machine at 175°C for 1 hr on balls of
  52-100 steel at a speed of 620 rpm
  diameter of the wear spot, mm, at loads, in kg
    1                                                    0.16
    10                                                   0.22
    40                                                   0.50
```

Other methods and processes are described in the foreign literature [173-187] for the processing of the petroleum base (hydrodesulfurization of separate fractions, depolymerization of polyolefinic oils with subsequent vacuum distillation, etc.).

The results of investigations have revealed that under high-temperature operating conditions, not only may synthetic lubricants be employed, but also petroleum oils may be used which have been subjected to intensive processing and cleaning.

Due to the plentiful supply and the relatively low cost of the petroleum base, high-temperature lubricants for TRD's manufactured on this basis are quite promising for the near future.

Prospective Lubricants for Turbojet Engines

With the high-temperature conditions prevailing in the friction points of the TRD's of future supersonic aircraft (450-550°C), the use of ordinary liquid lubricants of organic origin is not considered possible.

In this connection the possibility was pointed out a long time ago in the literature of using, for the purposes indicated, solid lubricants, gases, molten (liquid) metals and other substances. Reports concerning the development and testing of similar lubricants have been published during the past 10-15 years; however, there is no available published information concerning their use in turbojet aviation.

The first active work in this area relates to the period 1950-1955.

Beginning in 1956 the laboratory of the "General Electric" firm (in the state of New York, USA), while working on the design of bearings and lubricants, undertook the study of "air" bearings, possessing extremely small amounts of friction. Simultaneously the possibility was investigated of employing molten metals and glass as bearing lubricants at aircraft speeds of Mach 2.5 and at a temperature of 540°C. Bearings were designed which were lubricated with liquid metals, acids, gasoline and air. A great deal of attention was devoted to bearings with air lubrication [188].

The large-scale laboratory of the "General Electric" firm will investigate for a number of years the possibility of employing air bearings for operation under very high and very low temperature conditions, and also the use of lubricants in the form of molten metals and glass for very high speeds and pressures. The possibility is being studied of using glass, which has a specific melting point, and which in the molten state acts in a manner similar to other nonpolar liquids [189]. Different grades of glass in the liquid state may be employed as lubricants at temperatures up to 600°C under conditions when the bearing material can withstand these temperatures.

In order to avoid metal oxidation, fuel vapors are delivered to the bearings; however, in order to avoid wear it is better to spray oil into the bearings.

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Molten metals may be employed as lubricants at high temperatures [190]. For this purpose metals and their alloys with a low melting point are suitable, for example, sodium and calcium alloys (which fuse at 12°C) or calcium and cesium (fuse at 47°C). Gallium, indium and their alloys have a great deal of significance.

Liquid metals possess low viscosity and a flat viscosity-temperature curve. Almost all of them oxidize in air with the formation of a film or a powder, and therefore must operate under inert medium conditions, for example, in a nitrogen atmosphere.

An alloy of sodium and potassium was tested in steel bearings at a temperature of 120°C and with a shaft speed of 1750 rpm in an atomic electrical station in the USA. The bearings operated satisfactorily for a period of 5000 hr with radial and axial loads up to 15 kg [191].

Work is being accomplished in the development of lubricants [192] which are capable of operating in the temperature range of 550–650°C.

For a number of years highly effective bearings have been developed in the USA [193]; the operating surfaces of the bearings are separated by air or by other gases.

Dichlorodifluoromethane and other gases may be employed as lubricants for engine bearings [194]. The reaction of dichlorodifluoromethane with the surface of the steel forms a protective chloride film.

Investigations have revealed [195] that TRD bearings at temperatures up to 650°C may be successfully lubricated with a mixture of halogen-containing gases, for example, a mixture of CF_2BR_2, CF_3Br, SF_6. These gases significantly reduce friction and wear of alloys based on cobalt and nickel, while forming chloride and bromide films on their surfaces.

Significant attention is being devoted abroad to solid lubricants, such as graphite, molybdenum sulfide and molybdenum disulfide [194]. Graphite and molybdenum sulfide gave the best results during investigations in the laboratory. Both of these substances have high lubricating properties, are stable up to 600 and 400°C, respectively; and the graphite film has a self-restoring capability.

Molybdenum sulfide is the most interesting and effective. It possesses a low coefficient of friction, which decreases with an increase in the load, and is stable in air up to 450°C in a vacuum up to 1000°C, and in an inert gas medium up to 1300°C, and is capable of operating down to -185°C.

Cases involving bearing corrosion and wear were observed during the use of molybdenum sulfide [196]. The corrosion arose as a result of the inter-action of MoS_2 with water vapor; as a result, corrosion-promoting acids were formed.

It has been shown [197] that at 400-450°C molybdenum sulfide and graphite are oxidized by atmospheric oxygen and lose their lubricating properties.

Boron nitride is also among the solid lubricating materials with high lubricating properties. This substance has a laminar structure and provides for a low coefficient of friction of rubbing surfaces at high temperatures and pressures, high specific loads, in a vacuum, etc. [198].

It is believed that lead oxide is the best solid material for lubrication at temperatures to 540°C [199]. Lead oxide tests at 600°C also gave good results. The upper temperature limit of lead oxide is believed to be 870°C, above which the oxide disintegrates.

Cadmium oxide, sodium sulfate and cadmium sulfide [199] also possess good lubricating properties up to 540°C.

It has been noted [200] that titanium disulfide and titanium trisulfide may operate as lubricating materials in the form of powders up to 1000°C when there are no conditions which generate corrosion. In the presence of such conditions they may be employed in the form of liquid-dispersed phases up to 300°C. It is believed that titanium trisulfide is more effective than graphite and molybdenum disulfide.

Notwithstanding the great promise of gaseous and solid lubricating materials, they are still not employed in jet aviation; this is caused by the significant technical difficulties which arise in TRD design.

In the next few years apparently the most promising high-temperature lubricants for supersonic TRD's of the future will be lubricants based on fluorinated silicones of the alkylsilane type, the properties of which have been examined above.

Appendix 1

Quality indices of experimental specimens of ... type MS-b (R.-u) and MS-P obtained from different Soviet crudes.

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Appendix 1. Index of methods for testing synthetic oils by the Specification MIL-L-7808.

Indices	US Federal Standard No. 791	ASTM Standard
Density, g/cm³	—	D287-55
Kinematic viscosity at 98.9 and 37.8°C	305	D445-53 T
Temperature of:		
flash point	1103	D92-57
pour point	201	D97-57
Viscosity and viscosity stability at -54°C	307	—
Resistance to oxidation and corrosion at 175°C	5308	—
Corrosion on copper and silver at 232°C	5305	—
under corrosion on lead plates	5321	—
Volatility	351	D972-56
Antiwar properties on the Ryder machine	6508	D1947-64
Swelling of synthetic rubber	3604	—
Foaming	3211	D892-63
Precipitate formation	5003	—
Compatibility with other oils	3403	—
Trace of precipitate in the oil	3004	D664-52
Acid number and stability by the potentiometric titration method	5108	D1500-55
Color	—	D155-45 T
Density at 2.5°C	—	D1298-55

Appendix J
Conditions for oxidation and corrosion testing according to various specifications [52].

Indices	DERD-2497	Allison EMS-359	MIL-L-7808D, MIL-L-2533B	Prat & Whitney PWA-521 a)	MIL-L-25961, MIL-L-25336
Air supply, l/h	None	5±0.5	5±0.5	5±0.5	5±0.5
Volume of oil, ml	400	100±1	100±1	100±1	100±1
Duration of oxidation, hours	20	72	72	168	72 (48)
Oxidation temperature, °C	140±1	175±1	175±1	125±1	200±1
Area of piston, m²	11.5	13.0	13.0	13.0	13.0
cadmium-plated steel	11.5	13.0	13.0	13.0	13.0
cadmium alloy	—	13.0	13.0	13.0	13.0
silver-plated steel	—	13.0	13.0	13.0	13.0
silver	—	13.0	13.0	13.0	13.0
titanium	—	—	—	—	—

With recovery of condensate.

Appendix K. Requirements of specifications for oil quality after oxidation and corrosion testing [52].

Indices	DERD-2497 (Issue 3)	Allison EMS-359	MIL-L-7808D, MIL-L-2533B	MIL-L-25961	Prat & Whitney MIL-521 a)
Change in viscosity at 37.8°C no more than, %	±5	from -5 to 15	from -5 to 15	from -5 to 15	from -7 to 15
Acid number determination method	IP 139	ASTM 664-52	FS-VVL 791 915 105	Potentiometric to pH 11	—
mg KOH g, no more than	0.5	1.5	2.0	Optimal	1.0
Corrosion, change of mass, mg/cm²:					
copper	±0.2	±0.4	±0.4	±1.0	±0.2
cadmium-plated steel	±0.2	±0.2	±0.2	—	—
magnesium alloy	—	—	—	Optimal	±0.2
aluminum alloy	—	±0.2	±0.2	±1.0	±0.2
silver-plated steel	—	±0.2	±0.2	±1.0	±0.2
silver	—	—	—	±1.0	—
titanium	—	—	—	—	—

Titration to an end point corresponding to pH 11

Appendix 5. (Contd.)

Indices	Control 9B	Control 9C	Test methods
Oxidation tests			
temperature, °C at which the quantity of undissolved particles during air blowing with air reaches, %			
0.05	175 185	195 200	
0.5			
Thermal stability in a closed vessel			
temperature, °C at which the quantity of dissolved particles reaches 0.025 after 192 hours	275	260	Firm "Rolls-Royce" (RR1001)
Maximum temperature, °C, which can be achieved in 192 hours at preliminary treatment in a closed vessel (by the RR1008 method) before the onset of corrosion of steel during testing by the method RR1002.	230—240	230—240	Firm "Rolls-Royce" (RR1008)

Appendix 5. (Contd.)

Indices	Control 9B	Control 9C	Test methods
increase in acid number, mg/g	0.45	—	
change in viscosity at 37.8°C, %	1.0	—	
steel pieces with change in			
change in mass of plate, mg/cm²	—0.02	—0.01	
appearance	Unchanged		
increase in acid number, mg/g	0.35	—	
increase in viscosity at 37.8°C, %	1.9	—	
Shod tests for shear strength			
change in viscosity at 37.8°C after 24J cycles, %	a) +0.1 b) +0.2	—	Provided in specification DERD-2487 (Issue 4)
homogeneity	Meets specifications	Satisfactory	Corresponds to requirements of specifications MIL-L-7808 E and PWA-521 A
appearance	The same	The same	
at -54°C	Traces of molecular crystals		
at 260°C	Satisfactory	Satisfactory	Under any test conditions
at 15°C		—	
Miscibility with other oils			
Thermal stability at 260°C			Meets specification DERD-2487 (Issue 4)
change in viscosity at 37.8°C, %			
after x hours	—1.9	—1.5	
... .	—0.2	+3.4	
... .	—0.9	+1.2	
... .	—2.6	+3.6	

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13. ABSTRACT

This book describes briefly the construction and principles of operation of aviation gas turbine engines, their assemblies and friction points, and also the oil systems. Operating conditions of lubricants in these engines are discussed, as are the functions of oils as lubricating materials, the functions of operating liquids and cooling agents; technical specifications required of lubricants are discussed. Questions are discussed related to the assortment and quality of oils currently employed for aviation gas turbine engines and the requirements for oils of the near future. Methods are described for obtaining from petroleum and synthetics high-quality oils which possess high anti-oxidation, viscosity-temperature, anti-wear and other properties. Information is presented concerning additives which improve the operational properties of oils for aviation gas turbine engines. Domestic and foreign methods of investigating and testing oils under laboratory conditions, and also in special stands and devices are systematized and described. This book is intended for specialists associated with the construction and operation of aviation gas turbine engines, for petroleum engineers and chemists who are involved in the processing and preparation of the oils indicated and additives for them.

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Lubricating Oil Lubricant Additive Gas Turbine Engine						